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A Railroad Industry Critique Of the Modal Study

Prepared for

Association of American Railroads Safety & Operations

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Preface

The reader should be aware of two points with respect to this report. First, we emphasize that the report draws no conclusions about the 'safety' of spent nuclear fuel transport. Safety involves the combination of frequency of occurrence and the consequences of the occurrence. Our review dealt only with survivability (i.e. the occurrence of releases and not the consequences of releases). The questions AAR directed us to answer in our report all related to survivability of SNF transport casks. This focus led from the Department of Energy (DOE) position that the licensing tests provide more severe conditions than would be expected in real life and thus cask survivability is ensured at much higher speeds than Nuclear Regulatory Commission (NRC) design criteria impact speeds.

Second, there is no reference in the report to Appendix C, which is attached to it. We knew the findings of the review would be controversial and asked that the report remain a draft pending discussions and further assessment. Following completion of the draft report, analyses were undertaken to confirm the opinions developed in the original review. In addition, limited post-draft discussions with the authors of the reviewed reports and with personnel from the NRC led to the review of a number of additional reports. These *post-draft* activities have been attached to the report as Appendix C.

EXECUTIVE SUMMARY

Background

This report involves an evaluation of NRC test guideline for the transport of spent nuclear fuel. It involves a detailed review of the following two NRC funded reports:

1. Stammer, R.E., Abkowitz, M.D., Saricks, C.L., **Modal Study Transportation Accident Characterization.** Vanderbilt University and Argonne National Laboratory. Jan 1990.

2. Fischer, L.E., C.K., Chou, M.A. Gerhard, C.Y. Kimura, R.W. Martin, R.W. Mensing, M.E. Mount, and M.C. Witte. **Shipping Container Response to Severe Highway and Railway Accident Conditions.** NUREG/CR-4829, UCID 20733, Vol. 1 and 2. Lawrence Livermore National Laboratory. Feb 1987.

The purpose of this report is to better understand the testing spent nuclear fuel (SNF) casks undergo, and how that testing relates to forces that may be experienced in railroad accidents. The review is focused at two levels; 1.) the severity of the NRC tests in relation to situations that may develop in railroad accidents; and 2.) the survivability modeling and risk analyses performed with respect to severe railroad accidents.

Review Findings

<u>NRC Tests</u>

The NRC tests follow the recommendations of the International Atomic Energy Agency (IAEA). The testing calls for mechanical, thermal and water immersion tests to be conducted. The IAEA accident tests are intended to induce a level of damage to the package which is roughly equivalent to that which would occur in a very severe accident, but not necessarily the most severe of all conceivable accidents.

Our review led to a focus on the mechanical tests. Three tests have been defined to test a package's response to the mechanical effects of a transportation accident. Two are applicable to rail casks (an **impact** drop test and a **puncture** drop test); while a third (**crush** loading test) is only applicable to small packages.

In drop test I (impact test), which is described in detail in U.S. 10 CFR 71, the specification of an unyielding impact surface ensures that essentially all of the energy of the 13.3 m/s (30 mph) impact is absorbed by the cask (more specifically the sacrificial energy absorbing caps that designers use to cushion the actual cask).

The explanatory material for the IAEA Regulations also indicate that an impacting velocity of 2 or more times that specified in this test would be required to produce an equivalent load level when impacting a realistic yielding surface. IAEA's extrapolation of survivable speeds to realistic surfaces only considers its hardness. However, a realistic surface will also not be a perfectly flat surface as required in the drop test. The specification of a flat surface permits designs employing impact limiters only on end-cap locations to protect it from impact with the surface at any orientation. It is our opinion that a non-flat surface may reduce the effectiveness, or completely circumvent the impact limiters and apply concentrated loads directly on the cask surface, a scenario that may more than offset the damage mitigation effects of a softer flat surface.

Drop test II (puncture load) involves dropping the cask onto a mild steel bar with a circular cross-section diameter of 15.0 cm (5.9 inch) from a height of 1 meter (40 inches for U.S. 10 CFR 71). This test does provide loading from a non-flat surface; however, at a relatively low impact speed of 4.4 m/s (10 mph) and with a mild steel bar. It is not clear to us that this conservatively represents the types of concentrated loads that can occur in a railroad accident.

Drop test III (dynamic crush) is not required for certification of rail casks. In it, a 500 kg (227 lb) mass is dropped from a height of 9 m (30 ft for U.S. 10 CFR 71) onto a package supported on an unyielding surface. The inclusion of the test for small packages is based on the logic that they are transported in large numbers and in combination with other packages; and as a result demonstrate a higher probability of experiencing crush loads than large packages would. While large packages transported by truck (and to a certain extent by European-trains) may not be as susceptible to dynamic crushing as to impact loads, North American rail transport usually involves multiple vehicles with car characteristics that, in our opinion, demonstrate a high probability of dynamic crush loads upon derailment.

Survivability Modeling and Risk Analyses

In those areas of NRC testing where issues were identified, we looked to the modeling and risk analysis reports to allay our concerns. The DOE provided two reports to the AAR for this review: 1.) a survivability-and-risk-analysis study undertaken by Lawrence Liver more National Laboratories (LLNL), and 2.) a subsequent study undertaken by Vanderbilt University and Argonne National Laboratories (VU/A) which presented an interpretation of the LLNL findings with respect to damage expected under various real and hypothetical accidents.

The LLNL study derived loading events via review of severe accident reports conducted previously by others and again by their own team. Highway data were used to characterize wayside conditions and these data were also the basis of their estimates of the frequency of occurrences at various levels of severity. The severity of the loading events were then reassessed in light of the range of possible speed vectors and cask orientations that may be present in any given accident. Their analysis predicts that; given a rail accident occurs: 99.396 % result in no significant damage to the cask; 0.3948 % suffer ‘minor damage’; 0.196 % suffer ‘major damage’, and; 0.013 % ‘exceed definition’. When one factors in the frequency of railway accidents (measured in the millions of train miles) and the fact that relatively few spent fuel shipments are envisaged, their predicted risks become very small.

We have difficulty with the approach taken in the LLNL study because it largely views accident situations from the perspective of the regulatory test conditions. Impacts with flat surfaces were assessed extensively but concentrated loads and puncture loads and dynamic crush loads were not thoroughly explored—they were assessed to be of low magnitude and low probability. Their loading scenarios provide little direct information regarding the response of a rail transport cask subjected to concentrated impact loads. We believe that both the magnitude and probability associated with these types of loads under severe accident conditions was underestimated in their analyses. This largely resulted from their use of highway data to represent railway conditions and from what we believe is a misinterpretation of accident data in deriving event frequencies for vehicle frame/coupler impacts.

The follow-on VU/A study interpolated LLNL's speed and orientation variations of cask-impacts with flat surfaces of different hardnesses. It found that; for many cases, train speeds in excess of 100 mph would be required to reach damage thresholds for hard (not ‘unyielding’) surfaces. We could not trace their interpretation of the LLNL data.

Conclusions and Recommendations

The lack of any specification for retention of impact limiters is considered to be a shortcoming of the tests from the viewpoint of North American railroad accident conditions. We recommend NRC incorporate a test or design specification to ensure that impact limiters are retained following impacts at expected transport speed with a stationary unyielding object at an angle deemed to be the worst case for dislodging the device.

In addition, we believe that dynamic crush loads can develop in railroad accidents and that the IAEA crush test—now only required for small packages—should be included in railway cask testing (scaled up to produce impact energies of the magnitude expected in a railway accident).

We believe that the impact drop test provides a very conservative test of survivability for 30 mph impacts with flat surfaces; however, it is not clear how the test relates to real non-flat surfaces. Also, it is not clear that the puncture test provides a conservative test of survivability for the types of puncture impacts that may develop in a railroad accident. The reports provided for review did not provide adequate treatment of these issues to resolve them. We recommend a scope of research be undertaken to assess the survivability issues raised and to better estimate the risks involved in the transport of spent nuclear fuel by rail. The principal components of the research program should be:

1. an extensive cask survivability investigation (via either detailed finite element analyses or physical testing) which assesses concentrated loads, puncture loads and dynamic crush loads;
2. a review of tank car accident data to develop mechanical loading event frequencies, and, if required;
3. a survey of railway wayside conditions (replacing LLNL's highway survey data);

Parts of components 2) and 3) are required as input to component 1). However, a demonstration of survivability of severe accident loadings in 1) may reduce the number of hazards needing to be assessed for frequency of occurrence in 2) and 3).

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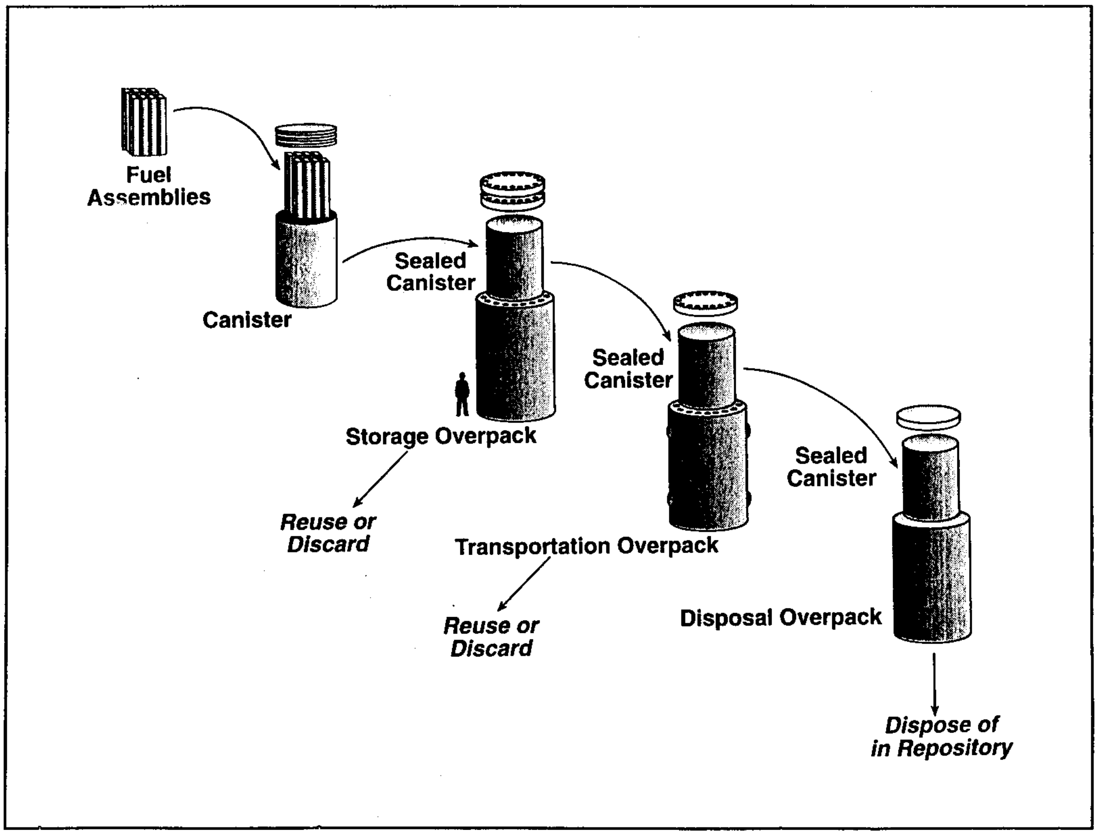
1. INTRODUCTION

1.1 BACKGROUND

The nuclear energy industry and government regulators of the industry have developed designs and regulations associated with the transport of spent nuclear fuel. Once loaded ***with spent nuclear fuel assemblies, an MPC will be sealed and***

loaded into a cask for each phase of storage, transport or disposal

Figure 1 illustrates the concept of a multi purpose canister (MPC) system envisioned for the transport and storage of spent nuclear fuel.



Once loaded with spent nuclear fuel assemblies, an MPC will be sealed and loaded into a cask for each phase of storage, transport or disposal

Figure 1 Illustration of the Multi Purpose Canister Concept

Source: US DOE "Multi-Purpose Canister System" DOE/RW 0426

The US Nuclear Regulatory Commission (NRC) specifies testing guidelines; one of which requires that any cask used to transport irradiated fuel survives a 30 foot drop test. The drop test accelerates the casks to a speed of approximately 30 MPH on to an unyielding surface. The Department of Energy (DOE) has conducted extensive testing that they believe shows that the transport cask is capable of withstanding a much greater impact than 30 MPH. The AAR would like to better understand this testing.

The types of questions that are of interest to AAR are as follows:

- what forces the casks would experience in a present day derailment scenario?;
- what is the likelihood of the casks being able to withstand these forces?, and;
- assuming that the future shipment would proceed in dedicated trains, what is the maximum speed of derailment, collision, or other type of accident as a result of a derailment, the proposed Transport Cask could survive?

Two reports in particular provide documentation of the analyses performed in assessing the survivability and risks of spent nuclear fuel transport by rail. They are:[i, ii]

> **"Shipping Container Response to Severe Highway and Railway Accidents Conditions" (NUREG/GR-4829), February 1987, by Lawrence Livermore National Laboratory. and;**
>
> **"Modal Study Transportation Accident Characterization" by Vanderbilt University and Argonne National Laboratory; January 1990**

Review of these two reports is an integral part of this assignment. Due to the high frequency with which we reference them, the two reports above are referred to simply as LLNL and VU/A respectively in the remainder of this analysis. The LLNL report is a major study that has been referred to by the NRC in its own publications (e.g. Transporting Spent Fuel - Protection Provided Against Severe Highway and Railroad Accidents, US NRC, March 1987). The VU/A study is a follow on to LLNL's report; taking actual accident events and trying to characterize them within a mechanical and thermal severity matrix developed in the LLNL study.

These two reports are not the sole treatment of the risks of rail transport of spent nuclear fuel. Another key document cited by LLNL which has been reviewed as part of this assignment is a report dealing with the severe accident loads: [iii]

> **"Severe Rail and Truck Accidents: Toward a Definition of Bounding Environments for Transportation Packages", by P. Eggers of Ridihalgh, Eggers and Associates, Inc, NUREG/CR-3499; October 1983**

In addition, the NRC undertook a risk assessment of its own in its original assessment of the adequacy of international test criteria for spent nuclear fuel casks. "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes", US NRC, NUREG-0170, December 1977. Their report and numerous other reports produced by suppliers and regulators were not reviewed in this present assignment.

1.2 APPROACH

To address the questions raised above, we have drawn very heavily on the work undertaken by LLNL (basically performing the same task for the US NRC). We follow through the LLNL report describing their methodology and assumptions. Where we would make different assumptions than LLNL, we discuss our rationale and; where feasible, estimate the impact on their calculations and conclusions. The VU/A study, which is not a stand alone risk assessment is reviewed in a separate section of our analysis.

The balance of our analysis is presented in 7 sections. Section 2 discusses the regulatory test requirements that a transport cask must pass in order to be licensed for transport of spent nuclear fuel.

Section 3 provides a brief overview of the LLNL report; illustrating the methodology and data sources it employed and summarizing its findings. The actual review of their report is presented in the 3 subsequent sections.

Section 4 provides discussion of LLNL's risk analysis and frequency estimates of loading events.

Section 5 addresses their estimates of severity of forces associated with the identified mechanical loadings

Section 6 discusses their analysis of the casks ability to survive the identified mechanical and thermal loads.

Section 7 discusses the VU/A report and raises a number of data interpretation issues.

Section 8 addresses the potential for various railroad operating practices and vehicle design parameters to mitigate the risks of spent nuclear fuel transport by railroads.

2. **CASK TEST REQUIREMENTS**

2.1 A CANDIDATE CASK

Figure 2 provides an illustration of the cask design selected by LLNL for their assessment (top part of figure), and an illustration of the details of typical penetration systems (bottom of figure).

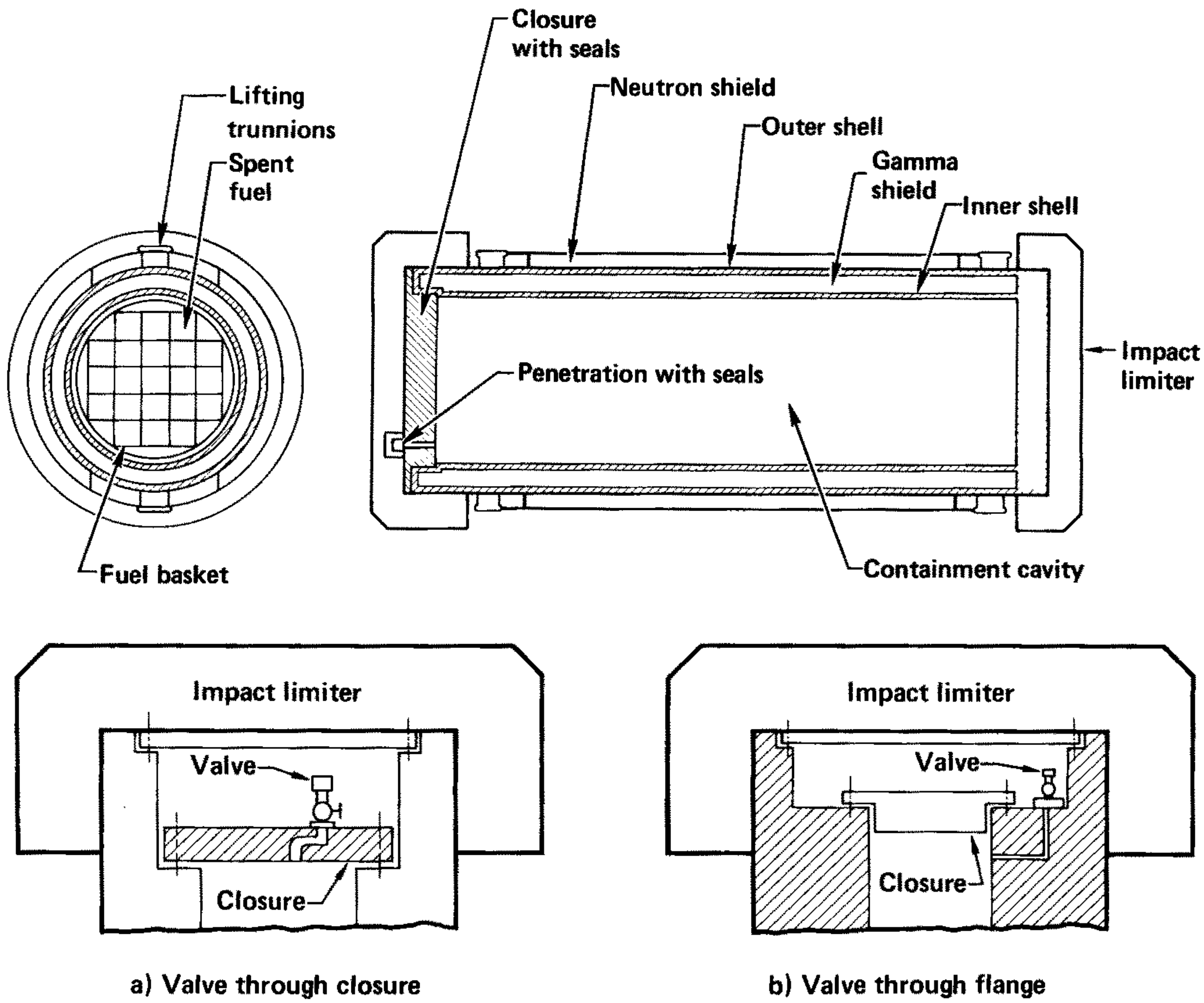


Figure 2 Typical Spent Fuel Cask (not to scale) [Source: LLNL Figs 1.1 & 3.3]

The casks are designed to provide the following protection against three potential hazards:

1. containment of potentially radioactive gases;
2. shielding from the contained radioactive material; and
3. maintenance of subcriticality if contents are fissionable products.

The spent fuel rods are held by a basket contained in the middle of the cask. Containment is accomplished by the structural strength designed into the cask body. As in this example design, stainless steel is typically used for its properties of high strength combined with flexibility. Containment integrity after exposure to thermal and mechanical loads is judged by the absence of permanent deformation to the cask and continued provision of a leak-tight seal.

Gamma shielding in this design is provided by the lead section sandwiched between the structural steel walls and neutron shielding is provided by a water jacket on the outer shell. The absence of lead slump demonstrates the integrity of the gamma shielding after exposure to thermal and mechanical loads. The cask is designed to meet post-accident radiation levels with the loss of the neutron shield.

Exceeding the criticality threshold requires a combination of factors that are exacerbated by release of the fuel from their individual chambers and infusion of water into the fuel chamber.

The impact limiters (much larger than scaled in the illustration) are intended to protect the cask from mechanical impacts. It is typically the sacrificial mechanism that absorbs the energy of the drop test while limiting the cask's deceleration ('g') forces to a level that avoids lead slump and internal fuel rod destruction.

2.2 THE IAEA ACCIDENT TEST CONDITIONS

In the early 1960s the International Atomic Energy Agency (IAEA) developed a set of standard mechanical, thermal and water imersion tests for demonstrating a package's ability to withstand accident conditions likely to be experienced during transport. These tests are periodically reviewed and updated by the IAEA Standing Advisory Group for the Safe Transport of Radioactive Materials (SAGSTRAM), an international panel of representatives from regualtory agencies, transportation authorities, the nuclear industry and packaging designers. The latest revision is contained within IAEA Safety Series No. 6, Regulations for the Safe Transport of Radioactive Material, 1985 Edition (As Amended 1990).

The information reported in this section is largely drawn from the IAEA regulations or associated interpretation guides. We comment on tests in relation to railroad vehicles in Section 2.3. **Where we offer comments in this present section we have differentiated our opinion by use of italic font.** Where issues are identified with respect to testing, it is possible that analyses may prove the concern to be unfounded. The LLNL report assesses the various loads to be expected in railway accidents and we pay particular attention to their treatment of the types of forces associated with the test issues raised here.

The IAEA accident test conditions are purely hypothetical in nature and are intended to induce a level of damage to the package that is roughly equivalent to that expected to occur in a very severe accident, but not necessarily the most severe of all concievable accidents. They are based upon engineering principles and judgements rather than the result of derivations made directly from specific accident analyses. Nevertheless, they are considered to be representative of very severe transportation accidents and the IAEA believes that the damage inflicted upon packages by these tests will exceed that associated with the vast majority of real accidents. Past experience and a number of risk and accident analysis studies have been cited in support of that conclusion.[iv]

We note that the LLNL and VU/A studies were conducted after those cited by IAEA. Since these studies were provided by the Department of Energy (DOE) in support of DOE's belief that casks passing the tests could survive normal rail accidents at speeds much higher than 30 mph, we presume that these studies are typical of the type of analysis referenced by IAEA in support of its similar belief. Thus, our conduct of this assignment involves an assessment of the applicability of the regulatory test conditions to railway accident conditions, and an assessment of the LLNL (and secondarily the VU/A) reports as a basis of concluding that the tests exceed the conditions expected in the vast majority of railway accidents and at speeds much greater than 30 mph.

2.2.1 Mechanical Tests

The IAEA classifies the mechanical effects of a transportation accident into impact, puncture and crush loading categories. Correspondingly, a total of three (3) mechanical tests have been defined to test a package's response to each of these types of loads. These three drop tests are as follows:[v]

1. In drop test I, a package is dropped from a height of 9 m (30 feet for U.S. 10 CFR 71) onto an unyielding surface in such an orientation as to suffer the maximum damage. This test is applied to all packages regardless of size, mass and density. The velocity of a package subjected to this drop test would be approximately 13.3 m/s (30 mph) at time of impact. The specification of an unyielding impact surface ensures that essentially all of the impact energy is absorbed by the structure of the package. The advisory material associated with the tests indicate that secondary impacts with the flat surface are also to be considered in assessing the damage and in determining the drop orientation that will inflict maximum damage. They note that this is most applicable to long slender packages with aspect ratios (length/width) greater than 5. The explanatory material for the IAEA Regluations also indicate that an impacting velocity of 2 or more times that specified in this test would be required to produce an equivalent load level when impacting a realistic yielding surface. This is due to the fact that the deformation of a realistic impacted surface will also absorb some of the impact energy.

   However, we note that a realistic surface will also not be a perfectly flat surface. We discuss the implications of this in later sections of our report.

2. In drop test II (pin drop or puncture test), a package is dropped from a height of 1 m (40 inches for U.S. 10 CFR 71) onto a bar rigidly mounted perpendicularly with respect to the plane of an unyielding surface. The package must be dropped in such an orientation as to suffer the maximum damage. The bar must be constructed of mild steel with a circular cross-section having a diameter of 15.0 ± 0.5 cm (5.9 ± 0.2 inch) and a length of at least 20 cm (7.9 inch). The length of the bar should be sufficient to cause maximum damage to the package, it should have a flat top surface and its edges should be rounded to a maximum radius of 6 mm

(0.24 inch). The velocity of this packge would be approximately 4.4 m/s (10 mph) at the time of impact with the pin. This test is applicable to all packages.

> *We have provided an illustration of the first two drop tests in* Figure 3*, roughly scaled to the type of cask assessed by LLNL. The puncture test is performed with the cask's impact limiters attached but with damage suffered from test #1. While the regulation calls for the bar to be long enough to cause maximum damage, it is a mild steel bar and may buckle before generating significant force. The buckling force for the regulatory pin has been estimated to be about 1.5 milion lb. If the cask design required a longer pin for penetration, its buckling load would be reduced. In queries concerning this test we had mixed responses — some indicating that a buckled pin was considered a pass, others indicating the test would be repeated in a different orientation. This test is the one that comes closest to representing an impact with a coupler or other structural component. We look to the analytic studies to determine if the test produces forces which exceed those that might develop in a severe accident situation.*

3. In drop test III (dynamic crush), a 500 kg (227 lb) mass is dropped from a height of 9 m (30 ft for U.S. 10 CFR 71) onto a package supported on an unyielding surface. The package is positioned such that it suffers maximum damage. **This test is not applicable to the rail casks in question; only to packages with mass of up to 500 kg (227 lb) and a mass density not greater than 1000 kg/m^3 (62.4 lb/ft^3).** The inclusion of the test for small packages is based on the logic that they are transported in large numbers and in combination with other packages; and as a result demonstarte a higher probability of experiencing crush loads than impact loads (E-627.4, IAEA Safety Series 7).

> *Our first reaction is that the lack of a dynamic crush test for rail casks may be an oversight. While large packages transported by truck (and to a certain extent by European-trains) may not be as susceptable to dynamic crushing as to impact loads, North American rail transport usually involves multiple vehicles with car characteristics which, in our opinion, demonstrate a high probability of dynamic crush loads upon derailment. We return to this issue in later sections of the report.*

2.2.2 Other Tests

The IAEA has developed a single thermal test for packages used to transport radioactive materials. In this test, a package must be fully engulfed in a hydrocarbon fuel/air fire having an average flame temperature of at least 800°C for a period of 30 minutes. The thermal test must be conducted under sufficiently calm and stable ambient conditions in order to ensure that an emissivity coefficient of at least 0.9 is maintained during the period of testing. The package

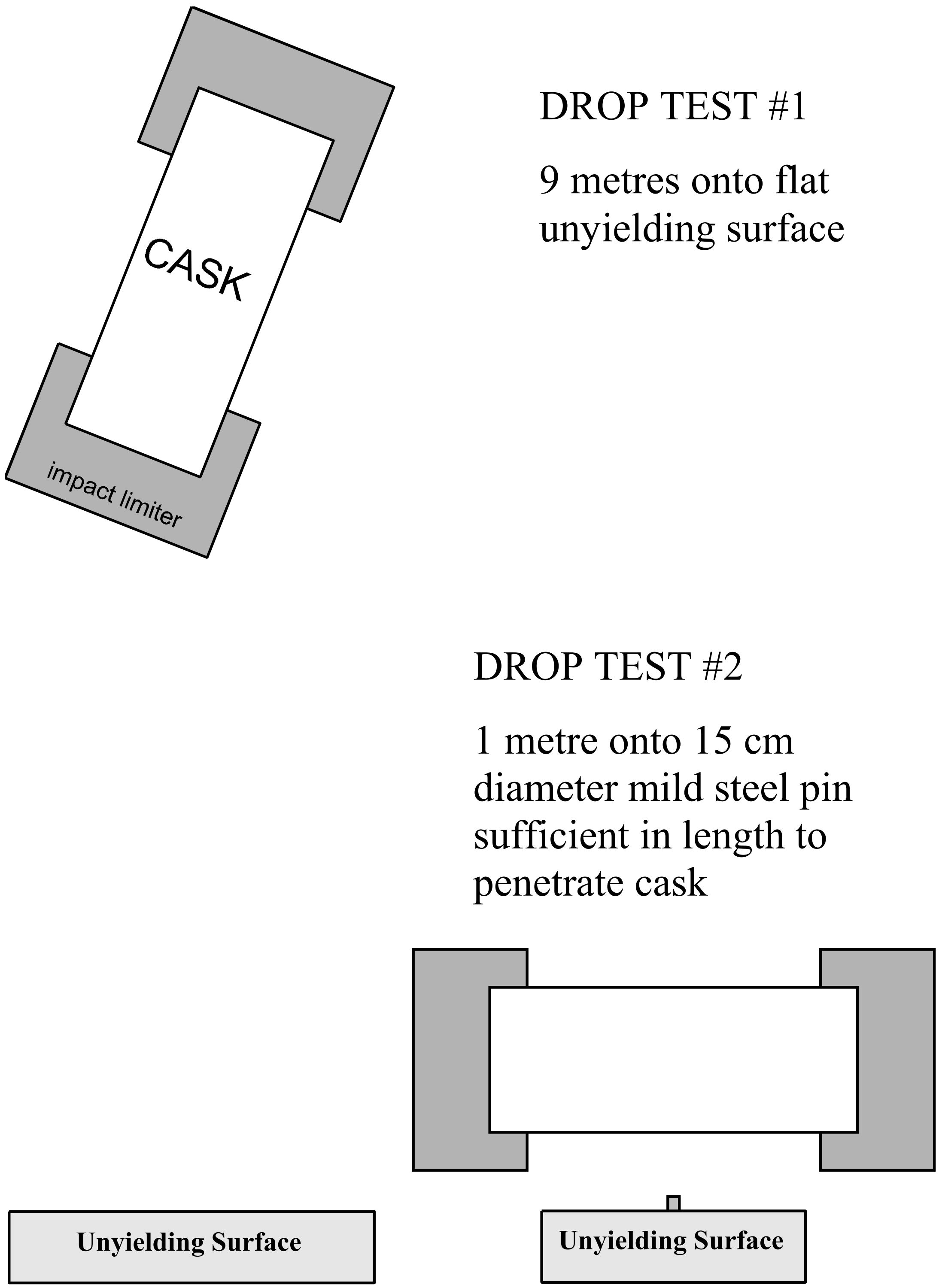


Figure 3 Illustration of Drop Tests 1 and 2 (Approximately to Scale)

must be allowed to cool naturally after the external heat input is removed. This test should be applied to a package that has suffered the maximum damage resulting from the mechanical test series.

> *The thermal test conditions are severe but may not represent the most severe conditions that may develop in a train accident. It assumes that the worst case is an engulfing fire.* [1] *With respect to the test parameters, flame emissivities higher than 0.9 are possible, and a value of 1.0 is often selected for conservative simulation analyses. Also, higher flame temperatures have been cited in relation to typical railroad commodities — Dennis's report (Sandia Labs: SAND77 0001) on accident severities indicates that most liquid hydrocarbon fuels fall in the range 1400° - 2400°F (760° - 1315°C), and that other fuels are lumped in the lower end of this same range. To a certain extent these latter factors are recognized by the IAEA. They indicate that other averaging effects (wind, cask thermal mass, temperature variations over time) and the unlikelihood of a 'fully' engulfing fire, more than compensate for the other non-conservative factors. We look to the analytic reports to substantiate these beliefs.*

The IAEA water immersion test specifies that a package must be immersed under a head of water of at least 15 m for a period of at least eight hours. The package must be oriented such that the maximum damage will occur. Compliance with these conditions may be demonstrated using an external gauge pressure of at least 150 kPa. Packages containing irradiated nuclear fuel must be subjected to an additional test consisting of immersion under a head of water of at least 200 m for at lest one hour. This test condition may be demonstrated by the application of an external gauge pressure of at least 2 Mpa.

2.2.3 General Aspects of Testing

The testing criterion as developed by the IAEA has been adapted by many regulatory agencies, including the U.S. Nuclear Regulatory Commission, for use in evaluating and licensing specific cask designs for the transportation of radioactive material. The regulations place demands on the design firm before it applies for testing. As noted previously, the regulations require that the tests be applied to a package such that the resulting damage is maximized. The package designers would be required to demonstrate to the satisfaction of the appropriate regulatory body that the worst case configuration for testing has been identified. In practical terms, this requirement requires careful analysis that often goes beyond the scope of the specific regulatory tests. Other acceptable demonstration techniques include scale model testing, references to and inferences from demonstrations of a substantially similar nature, calculations and reasoned arguments.

Finite element analysis techniques are widely used by packaging designers to support calculations related to specific failure modes and to simulate the dynamic response of a package and contents when subjected to the hypothetical accident test conditions. Such models are typically very detailed and must be shown to be capable of accurately representing the response

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[1] A torch fire has a concentrated flame close to the fuel origin. A jet fire is similar but involves a larger orifice and the flame is larger and further from the fuel source.

of the package. In demonstrating a package's compliance with the mechanical tests, analysts are advised by the IAEA to include specific investigations of stress, strain, instability and local effects when a package is dropped with an asymmetric attitude.[vi]

The IAEA require that the assessment of maximum damage must take into consideration the containment of radioactive material within the package, the retention of adequate shielding to maintain acceptable levels of external radiation and the maintenance of subcriticality when the payload is fissile material. Spent nuclear fuel would be classified as fissile material since the IAEA does not provide credit for fuel burn off (i.e. partial consumption of the original fissile material). Due to safety considerations, the IAEA recommend that payloads contained within packages undergoing full scale testing should not be radioactive. Rather, simulated contents should be carefully selected such that all relevant physical characteristics of the actual radioactive payload are accurately and adequately represented.

2.3 RELATING TEST CONDITIONS TO RAIL ACCIDENT CONDITIONS

The kinetic energy of the 197,000 lb representative rail cask containing 21 pressurize-water-reactor (PWR) spent fuel bundles travelling at 13.3 m/s (30 mph) is approximately 8.0 MJ (5.9 million ft×lb).[2] This is equivelent to the energy that must be absorbed by the impact limiter, cask and contents upon impact with the unyielding surface in a 9 m (30 foot) drop test. Typically, impact limiters used on casks for transporting radioactive material are designed such that they are capable of totally absorbing the impact energy of a 9 m (30 foot) drop test while limiting to a manageable magnitude the g (inertial) forces transmitted through the cask and contents as they decelerate. The force-deflection characteristics provided for the balsa wood impact limiters assumed for the representative rail cask have been designed to limit the deceleration of the cask and contents during 30 mph impacts with an unyielding surface to approximately 40 g.

Without the sacrificial deformation of the impact limiters, much higher impact loads would develop as the stiffer cask structure and contents deformed, elastically and likely also plastically, to absorb the energy. The implication here is that a cask withstands the energy and force transmission of an impact-limited 9 m (30 foot) drop test by design. Other impacts with the cask having similar energy content but occuring such that the impact-limiting devices are circumvented may result in cask damage, provided that the impacting object is sufficiently massive and is capable of generating sizeable impact forces while it deforms to absorb energy.

The energy that must be dissipated is the kinetic energy of the impacting bodies. The kinetic energy of a body is proportional to its mass and the square of its speed (specifically, $KE = 1/2\ MV^2$). Many rail vehicles have masses that are comparable, or greater than that of the fully loaded representative rail cask design (197,000 lbs). For example, the rail load limits for typical rail car classes are: 177,000 lbs for cars with 50 Ton nominal capacity (90% of rail cask mass); 220,000 lbs for cars with 70 Ton nominal capacity (112% of rail cask mass); 263,000 lbs for cars

[2] The type of cask design being discussed with the AAR weighs 250,000 lbs (127% of the candidate cask) and it would have to absorb 10.0 MJ of kinetic energy to pass the tests, since kinetic energy for a given speed is proportional to its mass.

with 100 Ton nominal capacity (134% of rail cask mass); and 315,000 lbs for cars with 125 Ton nominal capacity (160% of rail cask mass). Locomotives used in main-line service would typically weigh from 266,000 to 420,000 lbs (135% to 213% of rail cask mass) depending upon their axle count. It is evident then that individual vehicles in a train consist travelling well below typical freight railroad track speeds of 60-70 mph can achieve, and in fact exceed, the energy content implied by the 9 m (30 foot) drop test of the representative rail cask design. Moreover, the combined momentum of a block of cars in a consist would greatly exceed that energy level.

Figure 4 illustrates the relationship of kinetic energy with mass and speed and benchmarks the location of several objects noted in the discussion.

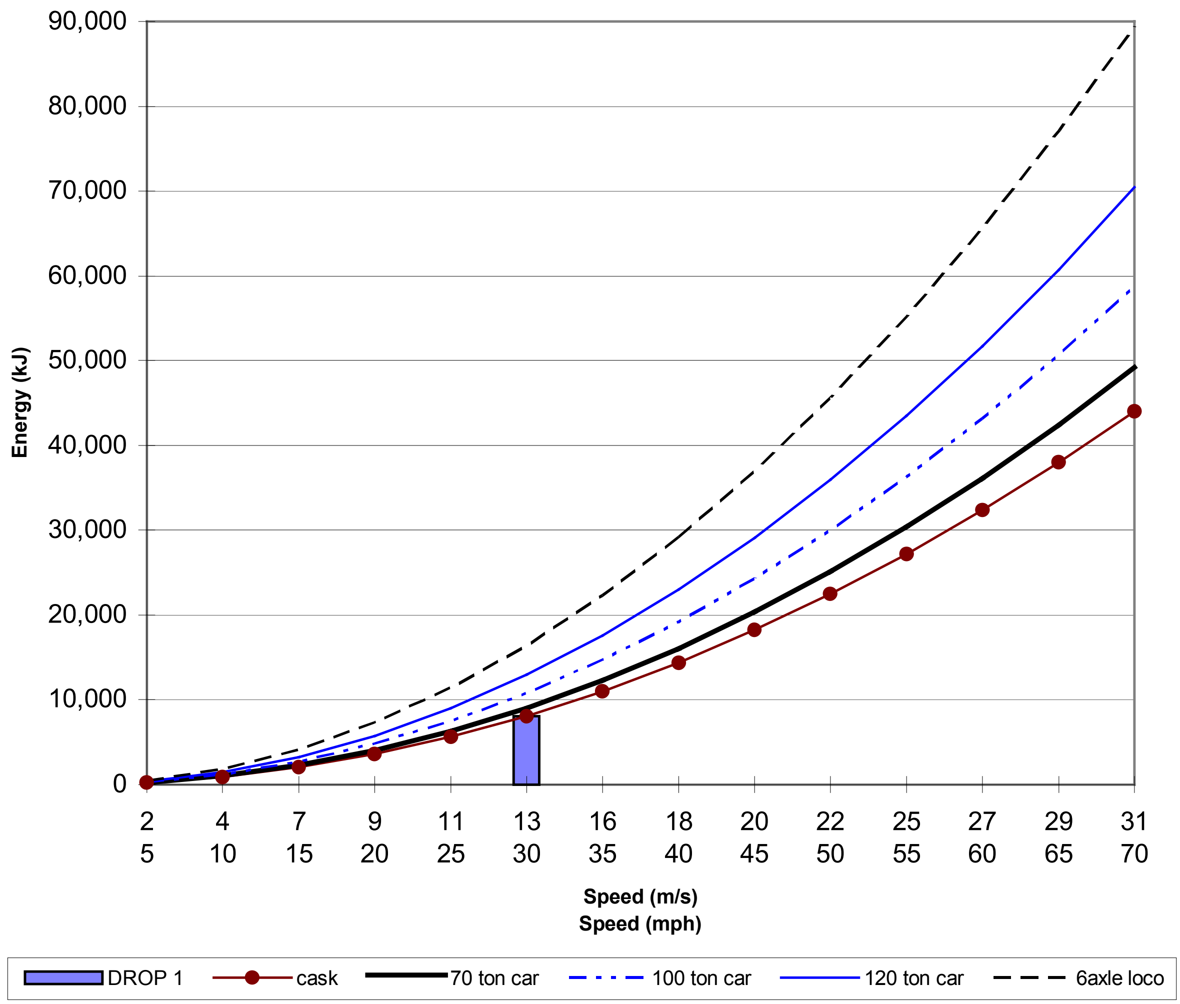

Figure 4 Comparison of Kinetic Energy of Representative Bodies

The existence of significant kinetic energy on impact is not by itself necessarily sufficient to cause serious damage to a cask designed to pass a 9 m (30 foot) drop test. The IAEA notes that the specification of an unyielding target surface results in a significantly more severe mechanical response than would be expected during a 30 mph impact between a package and a real surface or object. As noted previously, they estimate that an impact speed of twice that of the 9m (30 foot) drop, or even greater, would be required to achieve an equivalent force development on impact with a deformable surface or object. This is because both the cask and the surface, or object, being impacted will deform as energy is expended during the collision.

Using that estimate, real impacts with energy content of at least four times (i.e. $[2v/v]^2$) that of the 30 mph drop test would be required to achieve the hypothetical accident test loading.[3]

We note that the IAEA's extrapolation of survivable speeds to realistic surfaces takes a narrow interpretation of a realistic surface—it only considers its hardness. It is reasonable to assume that higher impact speeds can be accomodated without exacerbating cask damage if the impact surface deflects under force development. This is true whether the surface deflects eleastically or plastically. However, a realistic surface will also not be a perfectly flat surface. The extrapolation of results to higher speeds assumes that the actual impact loading situation is such that the impact limiting devices can function effectively to remove impact energy. The specification of a flat surface permits designs employing impact limiters only on end-cap locations to protect it from impact with the surface at any orientation. It is our opinion that a non-flat surface may reduce the effectiveness, or completely circumvent the impact limiters and apply concentrated loads directly on the cask surface, a scenario that may more than offset the damage mitigation effects of a yielding flat surface.

The IAEA drop test II (pin drop) is used to demonstrate a packages's ability to survive concentrated loads but at a low energy level. Further to the uncertainties identified previously with respect to the application of the test, we note that energies associated with test are low in comparison with expected conditions in a derailment. Impacts with surfaces having hard protruberances are likely events, both in the form of impacted surfaces such as bridge columns and rock outcroppings and in rail vehicles that can be expected to impact one another during multi-car derailment pile-ups. While the protrusions may not be as small in diameter as the test pin, they will often be harder and involve higher energy contents. Rail vehicles must be designed to be capable of transmitting large tensile and compressive forces through their sill structures. As an absolute minimum, any car must be capable of passing an 800,000 lb compression load test without incurring any plastic deformation of its frame structure. This is the requirement for the close-to-obsolete 50 ton car; current car designs must withstand 1,000,000 lb compression and 1,250,000 lb impact loads without suffering permanent deformation. In reality, the load transmission capabilities can be expected to exceed these minimum requirements and there exists a potential for development of impact forces with significant magnitude. A mitigating factor is the opportunity to remove impact energy through plastic deformation of the less stong structural elements comprising the rail vehicle's superstructures.

The kinetic energy content at the time of impact for a 1 m (40 inch) pin drop is only one ninth (11%) of that for a 9 m (30 foot) drop test for any given package mass. This reflects the

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[3] For any given mass, the kinetic energy is proportional to the square of the speed.

proportionate difference in potential energies for the two drop heights. In terms of impact velocity, the cask will strike the pin after accelerating to a speed of approimately 4.4 m/s (10 mph). This is only one third (33%) of the impact velocity that is achieved in a 9 m (30 foot) drop test. Although the impact energy of a 1 m (40 inch) pin drop test is nearly an order of magnitude lower than that of a 9 m (30 foot) drop, the structural loading of a package can still be quite severe in terms of localized plastic strain and the associated deformation of the package surface. This observation is premised on the assumption that the energy content of the impact is now being at least partially, and perhaps entirely, absorbed by the cask's structure rather than solely by sacrificial impact limiters. As noted in our previous discussion of drop test number two, the degree of cushioning provided by the impact limiter will depend upon the cask design and test arrangement.

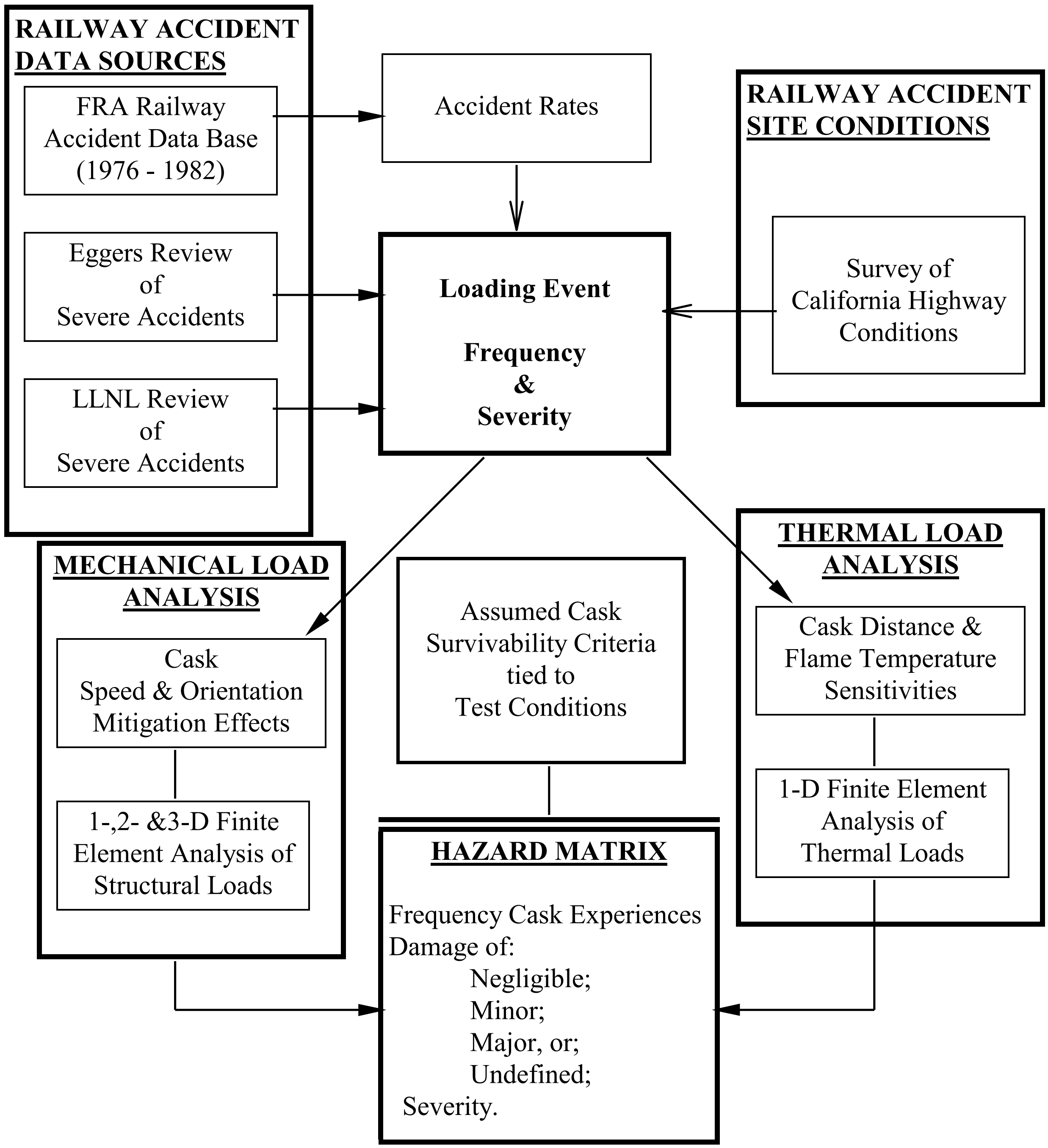
It is quite conceivable that impacts occuring between rail vehicles during a derailment pile-up can achieve an energy content exceeding that associated with a pin drop test. However, the extent of damage suffered by a cask will depend upon the location, size of contact area and the hardness and strength of the other impacting object. For example, the 15 cm diameter face of the pin used in the drop tests has an area substantially smaller than that of a coupler face and would therefore be expected to result in more severe localized damage than might occur during a coupler impact at the same speed. There is opportunity for impacts to occur between a cask and strong components of a rail vehicle's structure or a broken rail at higher speeds than 4.4 m/s (10 mph) and in orientations that could circomvent the impact limiters. The significance of such impacts should be considered by analysis and/or tests to ensure that the IAEA pin drop test provides an adequately severe mechanical loading that is not likely to be achieved during realistic rail accident scenarios.

It is specifically these issues of how the test requirements relate to actual accident conditions that were being addressed by LLNL in their report undertaken for the US NRC. The following sections provide an overview of their approach and findings, and a detailed review of the methodology and assumptions made in each of the components of their analysis.

3. LLNL STUDY OVERVIEW

LLNL's report presents a risk assessment of shipping spent nuclear fuel using truck and rail casks. The components of their railway analyses are discussed in more detail in later sections. This section provides an overview of their report. Figure 5 illustrates their methodology and data.

Figure 5 Illustration of the Principal Elements of LLNL's Analysis



As can be seen from the illustration in Figure 5 data from FRA's railway accident data base and reviews of severe accident reports—conducted previously by Eggers and again by their own team—were used to derive loading events. In their analyses, they considered 24 mechanical events and a range of fire durations for thermal events. Highway data were used to characterize wayside conditions. These data were also the basis of the their estimates of the frequency of occurrences at various levels of severity.

The severity of the loading events were then reassessed in light of possible speed vector distribution and cask orientations that may be present in any given accident.

The response of the containers to the various impact scenarios was predicted using a range of computer simulations and quasi-analytical treatments of the simulation results. Threshold criteria were developed for both mechanical and thermal loading.

The mechanical response of the cask is characterized in terms of a single mechanical parameter, namely maximum effective plastic strain within the inner shell of the transport cask. Three severity levels or ranges are assigned:

S1 - implies strain levels less than 0.2%
S2 - implies strains between 0.2 and 2.0%
S3 - implies strains between 2.0 and 30%

The S1 severity level corresponds to the strain to cause first yield as characterized by a 0.2% offset method. It is assumed that strains of this level will not cause significant damage and/or loss of radioactive material.

The S2 level is assumed to cause local distortion and some damage to the fuel rods and seals with some loss of gaseous material.

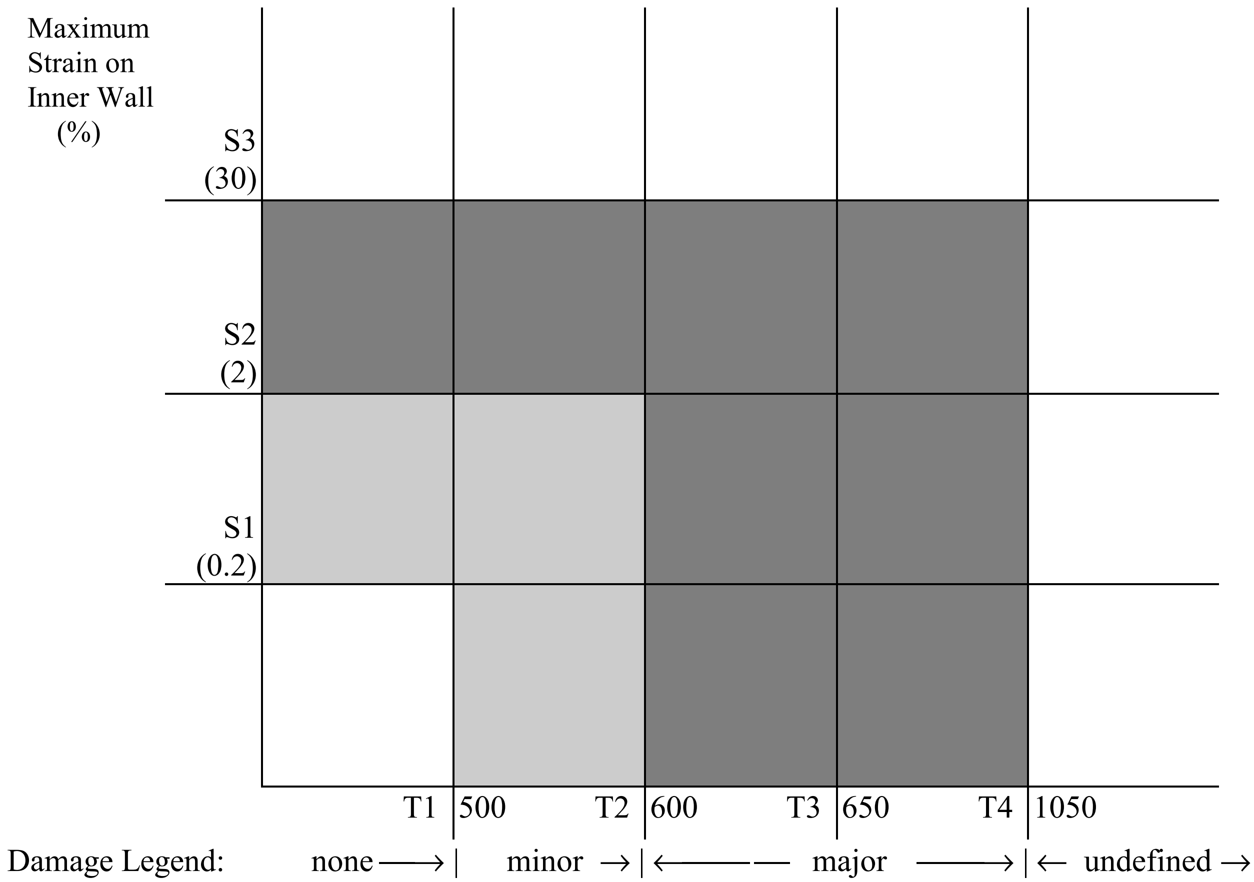
The S3 severity level represents gross plastic distortion of the cask such that seal loss and lead slumping occurs. The upper limit of 30% strain approaches the ductility of 304SS stainless steel.

The temperature at the middle of the lead shield was selected as the single measure of the effects of thermal load. The following four states were defined on the basis of the magnitude of the lead temperature:

A	100° - 500° F	water in neutron shield released (no significant damage)
B	500° - 600° F	closure seals degrade (minor damage)
C	600° - 650° F	lead melts, deformation of inner cask wall (major damage)
D	650° - 1050° F	fuel rods may burst (major damage)
E	above 1050° F	fuel integrity affected (damage exceeds definable range)

The analytic process culminates in a placement of loading events into cells in a loading severity matrix based on these mechanical and thermal thresholds (see Figure 6).

Figure 6 LLNL's Cask Severity Matrix



Based on: US NRC "Transporting Spent Fuel; Protection Provided Against Severe Highway and Railroad Accidents", March 1987

Their analysis predicts that; given a rail accident occurs, the fraction of all loading situations that would result in the various response cells is:

- 99.396 % in the lower left hand cell (i.e. no significant damage);
- 0.3948 % are in the 'minor damage' cells:
- 0.196 % are in the 'major damage' cells, and;
- 0.013 % are in the 'exceeding definition' cells.

When one factors in the frequency of railway accidents (measured in the millions of train miles) and the fact that relatively few spent fuel shipments are envisaged, the risks become very small. LLNL did not explicitly calculate the risks but noted that their estimated frequency of any damage, given an accident (i.e. 0.6%) were considerably below previous estimates of 20% made by the NRC in its environmental statement.

The following three sections of our report present a review of LLNL's report. Our review addresses the methodology and assumptions used in predicting the thermal and mechanical response of the shipping casks to the various impact scenarios. In particular, the modeling techniques employed are addressed for their adequacy and use of ‘state-of -the-art’ tools. The completeness of the report is discussed from the point of view of the worst case loading to be expected and the adequacy of the railway cask to survive the loading without releasing contents. The review is presented in three sub sections:

- risk assessment,
- loading environment, and
- cask survivability analysis.

Several areas of concern are identified in each area of the review.

4. **LLNL RISK ANALYSIS / FREQUENCY ESTIMATES**

4.1 METHODOLOGY

Risk analyses involve three components — estimates of incident frequency; assessment of the range of possible events that may derive from an incident; and assessment of the consequences to health, life and the environment of the various events. The LLNL study is somewhat focused on the middle step. It uses Federal Railroad Administration (FRA) accident data for an estimate of incident frequency and draws upon previously undertaken studies by NRC of the consequences of cask damage.[4] As most of the our questions also relate to the forces and survivability aspects of a cask subjected to a railroad accident, our review is also focused on the second stage of the overall risk analysis.

As illustrated in Figure 5 of the previous section, the analysis of loading events involved:

1. estimating specific loading scenarios that may arise in an accident situation on the basis of previous NRC studies and reviews of actual severe accident reports, and;
2. relating the loading scenarios to cask response by considering possible speed orientation and impacted surface hardness variations for mechanical loads and flame temperature, separation distance and duration of the fire for thermal loads.

The range of possible mechanical loading events was wider and more complex for the mechanical events than the thermal events. The types of mechanical loads and the associated frequency estimates are summarized in their Figure 2.5 titled 'Train Accident Scenarios', (repeated here as **Error! Reference source not found.** for easy reference). The are 24 individual load events at the end of the branches to the event tree. The two columns on the right side of the event tree depict the end probability of that particular load event happening *given that an accident has occurred* and denote whether it is an event that is considered to be potentially significant.

As can be seen from the final probability column, they estimate that over 47% of derailed cars do not impact with anything other than the roadbed; and only 0.8% experience impact with a coupler or significant frame member of other vehicles. Such values, in our opinion are totally unreasonable for severe accident scenarios. It may be reasonable, if one considers that many of the derailments included in the FRA statistics are not severe and involve only one or two cars. However, these were not the indicated source of the estimates.

The event frequencies shown in their Figure 2.5 for the more significant force levels show little resemblance to the referenced source data. While general reference is made to their own Appendix A, Eggers's data and highway data, we were unable to trace the basis of the key frequencies. Further comment on the key events is presented below.

[4] Accident frequency data from FRA railroad accident statistics for 1976 to 1982 were used. While these data are quite old, the significant reductions in accident rates achieved by the US railroads over the last decade make the LLNL data a conservative choice with respect to frequency of occurrence.

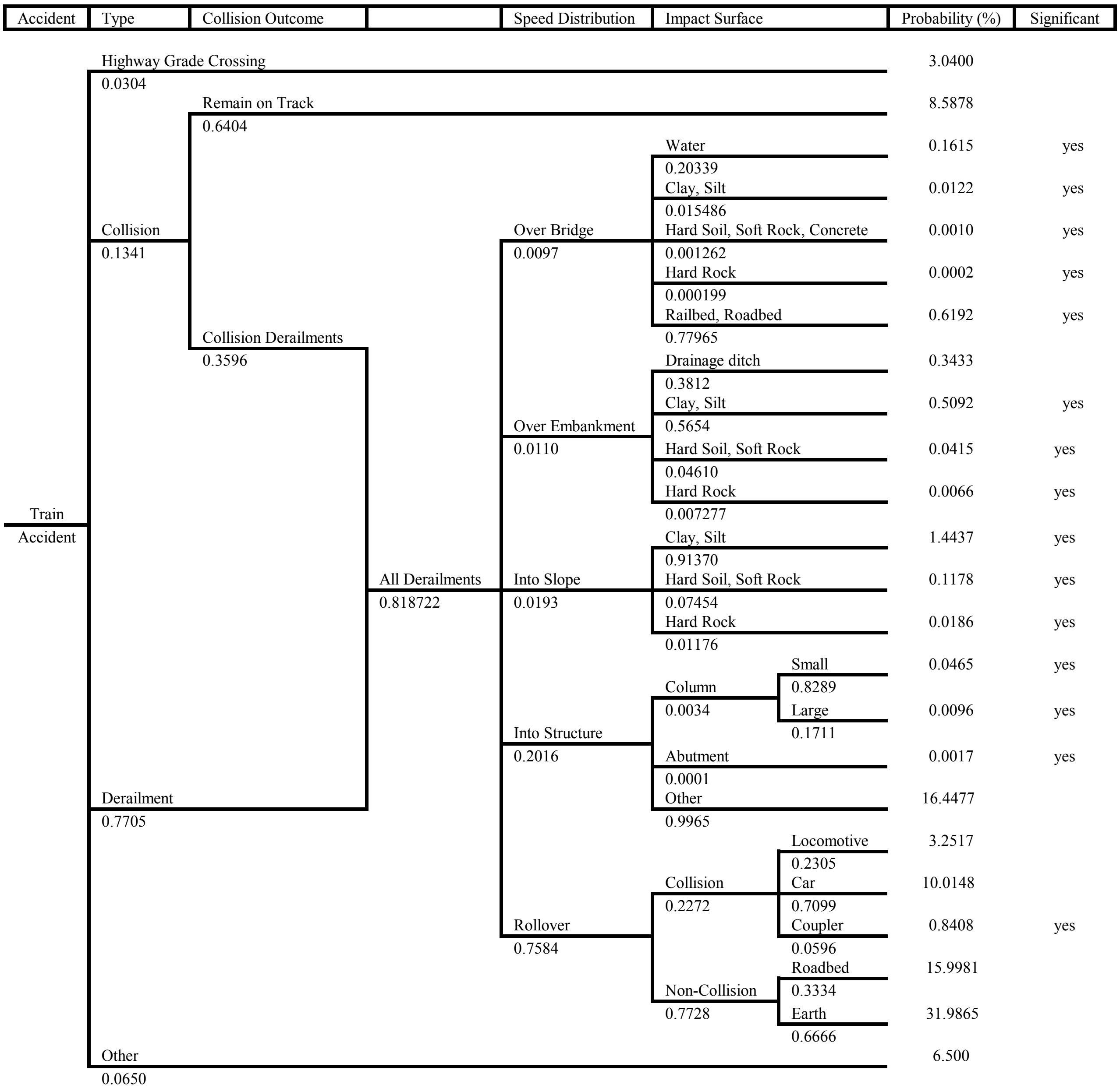


Figure 7 LLNL's Mechanical Loading Events for Railway Accidents

4.2 PROBABILITY OF CRUSHING

The frequency of incidence of crush loading was assessed as one-tenth that of impact loading (the basis of the assessment was unreferenced 'accident statistics'). These assumptions/findings are not intuitively obvious. Train accidents by definition involve multiple vehicles. The interaction of vehicles in the train after a collision or a derailment are more often than not subjected to crush loads in the radial direction (see car #10 or 21 in Figure 8 or the box car in the photo in Figure 9).

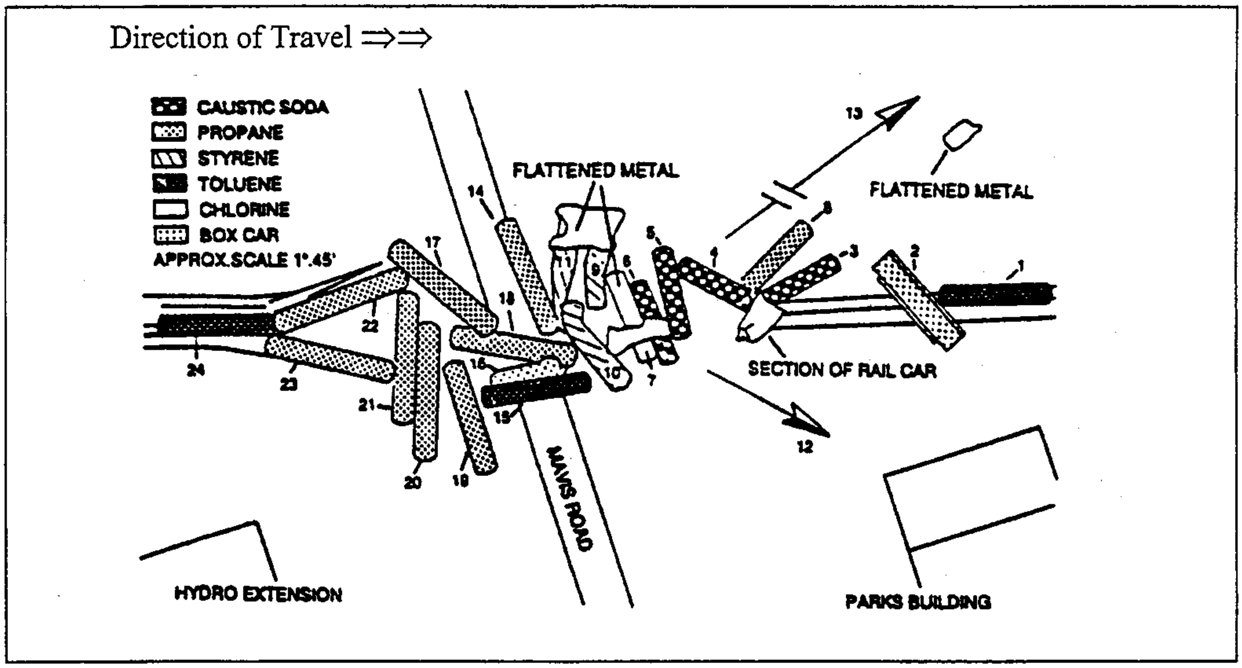


Figure 8 Car placement following Mississauga Derailment

LLNL's own report relates a rail incident involving extensive crushing damage to railway cars. Appendix A, relates the assessment of a severe derailment at Livingston Louisiana on September 28, 1982. The analysis of the accident report gives somewhat conflicting results:

> under 4.1.06 Evidence of Crushing:, the assessment is: ***"N/A"***
> while under 4.1.10 Evidence of Bending/Deformation of Support Members the assessment is:
>
> ***"36 cars destroyed by crushing impacts during derailment or by post accident fires".*** [5]

[5] An AAR reviewer's comment on our draft report indicated that these particular cars were more likely destroyed by post accident fire than by crushing impacts. It is not clear from LLNL's report whether this was known to them. In the absence of such knowledge, a conservative approach would be to consider the possibility of dynamic crush loads.

Even though this event is related in the report, the design assumes no crushing from derailment or collision dynamics. As noted in Appendix E (page E-17):

"the bounding crush load is a 200 ton locomotive that would rest on the rail cask by its sill." and, ***"Based on severe accident data, the frequency of occurrence of impact loads is at least a factor of 10 times higher than for puncture or crush loads. Therefore, since impact can generate higher loads and can occur more frequently, it is concluded that the impact loads dominate the potential loading environment and only impact loads will be considered further."***

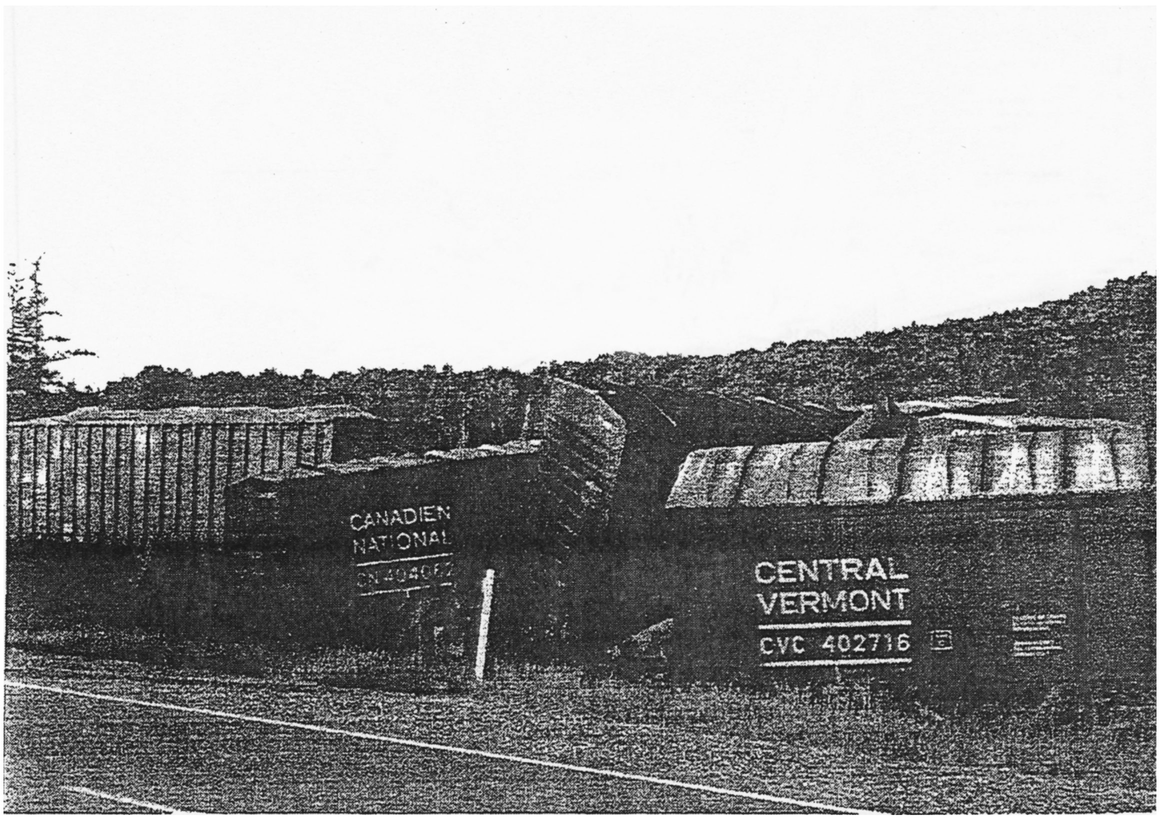


Figure 9 Photograph of Crushing in a Grade Crossing Collision / Derailment

Eggers also defined crushing as a static force that exists for an extended period of time. This may have emanated from earlier work by Sandia where crush was "arbitrarily defined to be 'essentially static forces acting on a container because of the latter's position underneath the truck'."[vii] There have been many accidents since the Livingston, LA derailment, which have resulted in crush loads and forces greater than those experienced at Livingston. The problem is not so much with this definition but with the fact that impact loads have not been expanded in definition in later studies to consider dynamic impacts against a cask that is resting against another surface (i.e. a dynamic crush load or a constrained impact load)

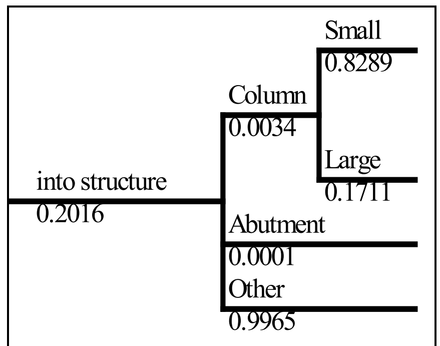
4.3 FREQUENCY OF EXPLOSIONS

Three of the 224 accidents in LLNL's Appendix A were explosions. This is a 1.34 % event frequency, and is higher than the frequencies they derived for 15 of their chosen 24 events. Eggers, their other cited source, had 19 explosions out of 176 accidents. Eggers also recorded the frequency distribution of missile weights involved. On the basis of these numbers we expected some discussion of its exclusion from the assessed events, but could not find one.

4.4 FREQUENCY OF NON-RAILCAR IMPACTS

4.4.1 Structures

Eggers's data has 17 of 168 (10%) accidents involving collision with structures ("bridges, buildings, storage bins or drawbridge counterweights"). LLNL use highway data for this category that has 20% impacting with structures; 99.65% of which are signposts and other items that produce negligible forces. Eggers's data would have been a more conservative choice.



LLNL's structural event tree

4.4.2 Falls

Eggers's review indicates 19 of 168 (11.3%) involving unbroken falls and another 37 (22%) falling down embankments. LLNL used 0.97% for falls off bridges and 1.1% for falls over embankments.

In estimating the probability of various ground conditions at the site of a derailment LLNL used the results of a highway survey. The authors cite a lack of railway data and note that railways cross similar terrain as highways in justifying this assumption. However, while railways may cross similar terrain, they take quite different routings from highways. Highways' passenger comfort considerations and high power to weight ratios lead to straight line route preferences. The rail mode with much lower power to weight ratios usually substitute curvature for gradient. Where highways tend to go over hills and down valleys, railroads go around them, or through hills and over valleys. As a consequence, railways frequently follow the path of rivers. In comparison to major interstate highways, one would expect railroads to make deeper and more frequent rock cuts and utilize more frequent and higher bridges to traverse similar terrain —. although the higher bridge frequency for terrain may be more than offset by the higher number of non-terrain bridges (e.g. intersections) used in the highway mode. In situations of flat terrain, the rail right of way is narrower than a highway and seldom has shoulders with any load bearing capacity. In addition, highways normally have barriers or guard rails to keep highway vehicles from falling into deep cuts. The are no such barriers and guard rails in the rail mode.

All of these factors would exacerbate the severity of derailment consequences over the LLNL estimates. Nonetheless, LLNL's comment on lack of available data is accurate. A sample survey was conducted after their study and independent of its initiatives. R.L. Banks reviewed 784

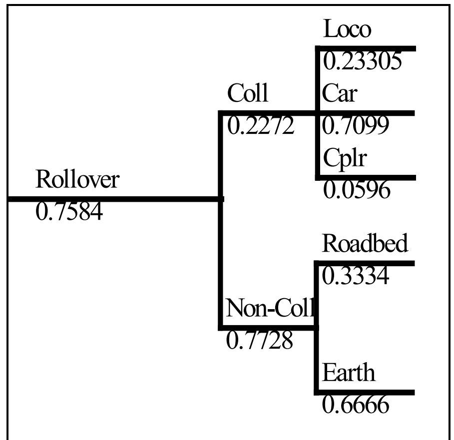
NTSB accident reports with the objective of identifying the type of terrain.[viii] The NTSB reports do not necessarily provide an unbiased sample of railway terrain — the reports address more severe accidents and the nature of the terrain may have influenced this severity in some cases. Nonetheless, it provides a conservative estimate of terrain. Their sample's distribution is:

bridges and	3.06%
tunnels	0.38%
cuts (whether rock or earth is not clarified)	8.55%
side-hill cuts (presumably a cut on one side, embankment on the other)	13.78%
fill (presumably with embankments)	40.56%
flat	32.53%

A conservative approach would be to apply these factors, that are in the order of 2.5 times the highway incidence of embankments and rock cuts. The highway data did not have an 'adjacent water' event. Only bridge accidents led to a water possibility. Water immersion of a damaged cask is one of the most extreme hazard conditions (enhancing criticality). Thus, even though the frequencies may be low, the consequences call for water to be a branch from the embankment event for train derailments.

4.5 FREQUENCY OF VEHICLE FRAME IMPACTS

Eggers's severe accident data was the quoted source of the estimated frequencies of impact with other vehicles in the train. LLNL assessed the relative frequency of a 'vehicle collisions' event, given a derailment has occurred, to be 17% (0.7584 * 0.2272 in their Figure 5.1). The fraction of these vehicle impacts that involve significant structural forces is reduced to 5.96% of these (or 1% of derailments). It is not clear how they derived these numbers from Eggers's report. Eggers indicate that 92 of 168 (55%) accidents in their review involved impacts by a moving railcar with other vehicles in the train.(pp. H-30) They also indicate that even those cars not impacting other objects while in motion, are subject to impact from other cars or components when stationary; and that a conservative assumption would be 96% are impacted. (pp. H-25)



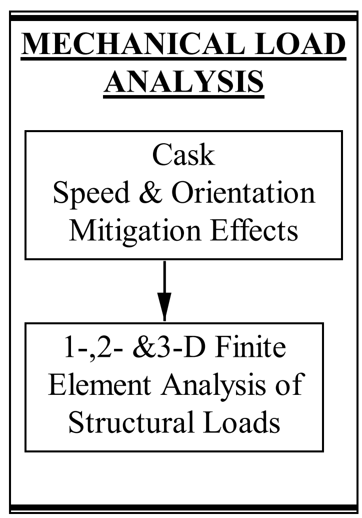
LLNL's Vehicle Impact event tree

Where multiple impacts are experienced in an accident, the conservative approach would be to assume the more severe ones. LLNL's own Appendix A describes the majority of the objects struck in derailment situations as "RR bed, RR car" (only two are described as only RR bed). For event probabilities they selected 3.5 times as many RR bed impacts as they did RR car impacts (0.77 vs. 0.22). Since, in their event tree only the 'RR car' impact events lead to a possibility of "potentially significant accident scenarios", the conservative assumption would be that all of these combined impact situations be assessed as vehicle impacts.

The assumption in the last level of the 'coll.' event branch that 6% of inter-vehicle impacts involve structural elements (designated 'cplr 0.0596') seems inordinately low. Eggers's data indicated evidence of coupler impacts in 6 accidents representing 6% of the 'moving vehicle impact' cases; and this is presumably the source of LLNL's number. However, Eggers' number is 6% of 55% of their severe accidents not 6% of 17% as LLNL assessed. Also Eggers's number is identified as coupler impacts; LLNL have combined into this category any structural component that can create a force level worth assessing.

One can get some insight into the frequency of significant force development in an accident situation by referring to hazardous materials (HAZMAT) data. Only HAZMAT cars are monitored for release and damage. FRA railroad accident data for the interval 1980 to 1994 indicate that an average of 29% of derailing HAZMAT cars released product as a consequence of accidents.[6] Of the releases involving tank cars, many are due to valve or piping damage rather than significant structural damage in the form of punctures. To get an estimate of the relative proportion of punctures we used data from an RPI-AAR tank car safety study.[ix] Data for the period 1980 to 1986 (i.e. after the introduction of shelf couplers and head shields) indicates a ratio of punctures to release from all causes (other than rupture due to fire) of 35%. Thus, the overall probability of a car experiencing significant structural impacts as a consequence of an accident may be estimated to be at least 10% (i.e. 0.29 * 0.35).

4.6 POST EVENT MITIGATION ASSUMPTIONS



Once the basic mechanical and thermal events were established, a range of possible values for a number of additional conditions (that influence the severity of the event) were applied. This section discusses the assumptions made in that stage of the analysis.

In deriving the derailment speed distribution for trains that will be involved in nuclear spent transport, LLNL used all mainline freight train derailments reported to the FRA. These data; in addition to now being 15 years old, reflect the mix of US freight train operations that are dominated by bulk trains, many in the mid west and western states. To assess spent nuclear fuel shipments in normal operating service one needs to consider the relative performance of mixed freight trains primarily involving regions where spent nuclear fuel will be transported. The FRA data does not provide details on the type of freight train involved in derailments but it does monitor hazardous materials involvement in accidents. Hazardous materials shipments are largely transported in mixed freight trains and their location distribution is skewed to the Eastern

[6] The industry has realized a decline in this ratio of damaged/derailed tank cars over the last 10 years. This is an indicator of car improvements rather than reductions in derailment severity, the average of the ratio is a conservative number with respect to expected damage ratios for present tank car designs.

and mid-West states.[x] The speed distribution of derailing trains where HAZMAT cars are involved is higher than that of an all-freight-trains sample.

The approach Eggers took was even more conservative. They used the speed distributions of their subset of severe accidents. However, it should be noted that Eggers also adjusted their accident rate estimate to recognize that severe accidents are a subset of all FRA accidents. They estimated that their severe accident category represented less than 12.5% of the FRA-reportable accidents (pp. H-22). We consider Eggers speed distribution to be more consistent with LLNL's approach than the full FRA data set they used.

Figure 10 presents a comparison of the distribution of train speed for class 1 mainline freight railroads, for only those derailments that involve hazardous materials cars and the subset of severe accidents selected by Eggers. From Figure 10 it is seen that 66% of all class 1 train derailments are below 30 mph, whereas the threshold speed for 66% of HAZMAT train derailments is 40 mph and for Eggers's severe accidents it is close to 50 mph. The data used by LLNL had 81% of derailments less than, or equal to, 30 mph.

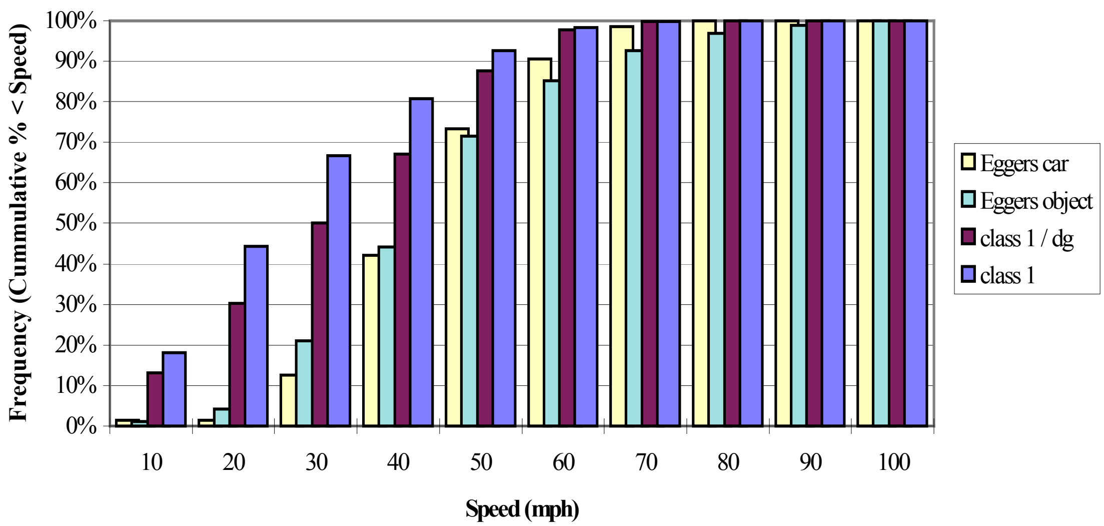


Figure 10 Comparison of Normal and Severe Accident Speed Distributions

Train derailments are also highly skewed to the class of track involved. Many of the low speed derailments occur on FRA class 1 and class 2 tracks. While the specific routing of spent nuclear fuel trains is not presently known, it is likely that the dominant track segments used will be class 3 or better. Both of the above factors influence the frequency of occurrence as well as severity of accidents. While HAZMAT freight trains and higher FRA track classes involve higher speed derailments, the rate of derailments is expected to be lower. The data should be assessed from the viewpoint of the most likely routings. A more extensive assessment of railway accident data is required to more accurately, and more conservatively, estimate the risks of spent nuclear fuel transport; and estimation of the specific risks is the prerequisite to managing that risk.

The use of all data to derive speed distributions for events that are tied to severe data is somewhat inconsistent. The coupler event for instance is a mechanical loading event that is further assessed for severity by applying the speed distribution. For LLNL's data, the 0.8% of loading events is further mitigated by the fact that 35.5% of these are determined to happen at derailment speeds of less than 11 mph.

Other potential mitigating factors that are incorporated in the LLNL analysis are: impact speed vector distribution, cask orientation distribution and derailment-car-position distribution. The application of these post event mitigation factors is summarized in LLNL's Table 5.11. It appears that a conservative assumption was made for position-in-derailment effects. It is stated that each subsequent car in a derailment derails at a lower speed. Other studies have assumed a linear reduction of speed from the accident speed to zero over the number of cars involved; however, LLNL have taken the conservative assumption that the cask will be at derailment speed when impacts occur. For the coupler impact event they have also selected a conservative distribution for speed vectors — all are assumed to be head on.[7] However, derailment speed is further mitigated by the cask orientation assumption for this scenario — uniform distribution between 0° and 90° radially from the cask cylindrical center point (see the lower part of orientation geometry of object striking cask

Figure 12 discussed later). This reduces the severity of impact further.

One must consider that the original observations of coupler impacts have already incorporated this distribution (but for a different car type). The "near miss" situation posed by a 90° orientation would not have left evidence of a coupler impact in the first place. A portion of each speed range is eliminated from consideration due to the orientation assumption. For example 33% of the orientations require an impact speed attained in only 1% of the accidents.

To estimate the influence of this effect; we considered tank car punctures as an example and for illustrative purposes, made the rather arbitrary assumption that the tank car puncture threshold is related to the radial impact angle in the same manner as LLNL's prediction of 0.2% strain at the inner shell of the cask.[8]

On this basis, the effect on the 0.8% probability of load occurrence of coupler impact is to reduce its probability of occurring from 0.8% to about 0.2%. The result is that; although Eggers's final-

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7 While the 'head-on' assumption is conservative with respect to impact-speed mitigation, it is not clear that it is conservative with respect to cask damage. The head on scenario was for a locomotive sill offering a 10 foot wide distributed load. A coupler or any change in orientation of the impacting locomotive frame would have led to a much more concentrated load.

8 The puncture-equivalent to LLNL 0.2% strain predictions are:

- an impact speed of at least 11 mph is needed to get evidence of puncture at 0° orientation;
- an impact speed of 16 mph is needed to get evidence of puncture at 45° orientation and;
- an impact speed of 150 mph is needed to get evidence of puncture at 90° orientation.

event observation of 6 of 168 (3.6%) accidents was quoted as a source, it was incorporated into the methodology such that it became about 1/18th of its original value. The problem is not so much with the methodology—derailment-position, speed vector and orientation will be factors—but with the interpretation of the accident data. The observed final state should be worked back through the post-loading-scenario mitigation factors to derive the frequency of mechanical loading events that must have existed to get the final frequency of observation.

As noted previously, it appears that they also included all frame contacts in this category. We would consider the frequency of frame contacts to be at least as likely as coupler contacts. From our earlier review of HAZMAT release/puncture incidence, we would select a 10% frequency of significant structural impact occurring in a derailment situation. On this basis, the frequency of LLNL's defined 'coupler impact' as an event (before other mitigation of its severity) is understated by a factor of 50. In the context of their analyses, we would raise this event frequency by a multiple of 50. Thus, the 0.84% frequency becomes 42.0%. Of the remainder of "roll-over accidents" we would allocate 2% to roadbed and the remaining 35.8% to car and locomotive body components other than frames/couplers.

It is important to note that the relative speed of impacts between vehicles in the train is a complex event. As discussed in more detail later, derailment mechanics are not well understood. Review of post accident vehicle orientation and damage offers some insight, but it is extremely difficult to predict what types of forces developed (and more importantly what factors influence their development) from post accident orientation.

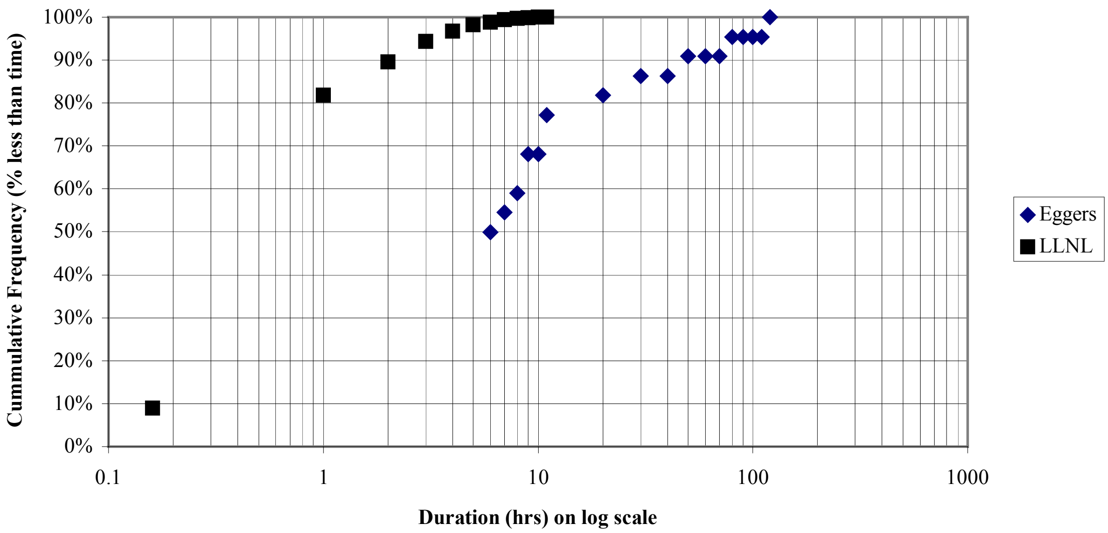
4.7 THERMAL EVENT FREQUENCIES

LLNL used a Monte Carlo simulation model originating with Sandia National Laboratories[xi] to predict fire frequencies and durations as a consequence of derailments. While Eggers's report and their own review of accident reports were cited in the mechanical loading analyses, they were not referenced in the thermal analyses. Nonetheless, these other sources did contain real observations of thermal events associated with severe railway accidents.

LLNL's simulation based distribution of fire durations predicted 81% to last less than 1 hour and 99% to be less than 7 hours. Eggers's fire duration distributions on the other hand, had 50% of the durations at less than 11 hours and 99% less than 130 hours. LLNL's Appendix A includes a report of a post-derailment fire that lasted 8 days. LLNL's and Eggers's fire duration distributions are illustrated in Figure 11 with fire duration shown on a log scale.

Eggers's distribution of durations is obviously a more conservative choice (more than 10 times the duration of LLNL's model at most data points). Also, Eggers's severe accident data included two torch fires that LLNL did not assess. We were unable to obtain a copy of the referenced Sandia source of LLNL's Monte Carlo model and LLNL's report provided no discussion of their selection of Sandia's simulation based data in preference to Eggers's accident data. A key factor in the simulation would be the assumptions on fire fighting efforts (which LLNL indicate is part of the model). The response is situation dependent. In some situations, if there are dangers posed to response personnel from ignition of other commodities, response personnel may stay away from railway fires and let them burn out. Their efforts are directed to evacuation of anyone in an identified hazard zone. This assumption would significantly alter the fire duration results derived via simulation. It is possible that the risks of radioactive release may alter this approach but we could not find evidence that the risk tradeoffs have been evaluated. As discussed later, the preferred method of risk mitigation of this hazard, if it is determined to be significant, may be via consist makeup restrictions.

Figure 11 Fire Duration Distributions



Again it should be noted that; as with the structural loading scenarios, Eggers's data represents a sub-class of severe accidents rather than typical accident situations. If their severe accident cases were incorporated in a risk analysis, the frequency of occurrence would have to be adjusted downward.

Recent work by Raj also cites a lack of data for fire durations and assumes a distribution similar to LLNL's with the 90th percentile duration at 2 hours. [pp. 5-10, vol. II[xii]]. If this assumption is derived from experience or literature reports that are independent of LLNL and their Sandia reference, it may be that Eggers's data are extreme examples. We are not in a position to draw any conclusions in this regard, other than that a wider based survey of post derailment fire situations is called for. Also, related to the frequency of occurrence is the base frequency of any fire given a derailment. LLNL selected 1% of derailments leading to fires and we are aware of other studies that have used a similar number. Raj cites RSPA data on hazardous material accidents that show 2.1% of these accidents result in fire. As both the frequency and severity of fires can be expected to be higher in hazardous material accidents, the risk may be addressed by using buffer cars to distance the transport cask from the front and end of the train which may be exposed to such cars in a collision situation.

4.8 POSSIBLE MODIFICATIONS TO THE RISK ASSESSMENT

4.8.1 Revised Frequency Estimates

On the basis of the previous discussion we would alter many of the frequency estimates in LLNL's train accident scenario. Our revision of their mechanical loading event tree is such that where LLNL estimated 3.8% of the possible events occurring in severe accidents to be 'potentially significant' thereby justifying detailed analysis; we would estimate from the same data that more than 50% fall into their 'potentially significant' category and warrant detailed analysis.

As noted, LLNL further mitigated the significant events through speed and orientation distributions such that only 0.4% developed into significant loads. A rigorous analysis of the loading situations and severities given a severe accident, is beyond the scope of our review. However, we would select speed distributions and loading situations that would result in less mitigation from these effects than LLNL's assumptions.

On the other hand, we would significantly downgrade their accident frequency estimate. The accident rate per car-mile depends on the consist that the MPC will be transported in and the operating practices involved. The LLNL analysis was predicated on the risks posed by a normal rail transport environment, and its findings are one of the factors that influenced DOE's belief that the casks are safe for transport without operating restrictions. While we have found many assumptions and limitations to the LLNL analysis that would deter from its findings, our purpose in this section is make an estimate of the consequences of making our suggested modifications to their assessment but remaining within their overall framework. Thus, for present purposes we consider FRA accident data. However, where LLNL used 11.9 per million train miles, we would use the lower rate established over the last decade (estimated though not substantiated to be about 3.5 per million miles) and apply Eggers's factor of 0.125 as the estimated ratio of severe accidents. We also assume a train length such that the cask car is (all cask cars are) derailed if the train it is (they are) transported in is involved in a severe accident. This assumption would only be valid for short trains but is made simply as a conservative assumption which simplifies the calculations. It was also LLNL's inherent assumption. On this basis, the expected frequency of cask involvement in a severe accident is:

$$3.5 \times 0.125 = 0.4375 \text{ per million car miles.}$$ [9]

To put this in context of the anticipated spent-nuclear-fuel transport program, we assume that 10,000 shipments will be made and each shipment will travel on average 2,200 miles by train (i.e. 22 million car miles are expected). From the above accident rates, one can expect:

- 77 loaded casks to be involved in accidents;
- 10 loaded cask to be involved in severe accidents;

[9] There would be an equivalent exposure for the empty return transport which is assumed to pose no risk. The assumption that all cask cars derail if its train derails permits the substitution of car-miles for train-miles (i.e. 6-car trains would involve 1/6th the train miles but 6-times the number of casks in a train derailment).

- 5 loaded casks to experience mechanical loading events that should be assessed for consequences, and;
- 2.5 loaded casks to be exposed to post derailment thermal events.

The above discussion has dealt with mainline derailments. There is also an element of risk associated with non mainline activities. Exposure to fires, explosions and collisions also exists in yards and sidings. While one would expect the severity of collisions and derailments in these areas to be less severe, we have observed that the FRA accident data contains numerous records of derailments in other-than-mainline track that occur at speeds above 30 mph and involve equipment damage above $100,000. These records should also be considered in the derivation of accident frequency and severity.

There are also instances in the FRA data base of significant equipment damage occurring and/or large numbers of cars derailing at speeds of less than 5 mph. Since the data base is largely derived from hand prepared accident report forms filled in by the operating railway, there is potential for errors and omissions at the point of original reporting, transcribing or final coding.

We believe that the RPI/AAR tank car accident data base provides a more detailed assessment of damage. Also, the FRA accident records for HAZMAT accidents are more frequently derived from more rigorous investigation methods than are other accidents. It may be desirable to make more use of these data bases and base an analysis on this subset of accidents in determining the risks that spent nuclear fuel casks will be exposed to.

Neither LLNL's nor our revisions to their estimates constitutes a rigorous risk analysis. However, the level of difference of interpretation of available data would indicate that a more rigorous assessment is warranted.

4.8.2 Enhanced Modeling Tools

If one wishes to derive knowledge on how to best mitigate the risks through modified operations it will be desirable to incorporate operational parameters into the risk modeling exercise. Two approaches have been taken to derive the type of detailed parametric relationships necessary to assess the effectiveness of operational and design modifications. One involves statistically based parametric models of derailment severity, the other is a physical simulation model of derailment mechanics. Examples of the two approaches are discussed below. Each has its limitations and a combination of the two is probably the best approach.

Saccomano has proposed a statistically based derailment model that can be calibrated with accident experience specific to a given route.[xiii] The model is also sensitive to train make up factors such as length, speed, car blocking and position in train. The formulation of the model is fairly complex and the reader is referred to the reference for details. The equations are summarized below:

$$PN(X) = \frac{p(1-p)^{(X-1)}}{(1-(1-p)^{RL})}$$

where:

- PN(X) = the probability that X cars derail, given a derailment was initiated at a specific location in the train;
- X = 1,2,3 ... RL;
- RL = number of cars in residual train length;

and p is a logit function of:

$$p = \frac{e^{Z}}{(1 + e^{Z})}$$

with Z taking the following form, with coefficients being derived for a specific route segment:

$$Z = A + B * Log(speed) + C * Log(RL) + D * (cause1) + E * (cause2) + \ldots\ldots$$

where A-through-E are coefficients of determination specific to the route and train makeup.

This type of model allows one to input the specific characteristics relevant to a known routing and train make up. The limitation of this type of model is that it is statistically based and predicting events to the extent that their influence is discernible. Many of the parameters of interest are either not present, or not reported in enough volume to develop a statistically significant relationship.

Some of the relationships of interest follow known engineering principles (e.g. train length, braking ratios) and do not need statistical data to generate reasonable coefficients. Models such as the one developed by Yang et al.[xiv] fall in to this category. Although many of the sensitivities captured by this type of model can be demonstrated in much simpler and faster spread sheet based models.

A more detailed discussion of derailment modeling and force prediction has been presented to the AAR by Moynihan et al.[xv] The following addresses some of the key factors.

Rail vehicle derailments and impacts are dynamic events that involve conversion of large amounts of kinetic energy through dissipation by friction, absorption through structural deformation, momentum transfer and conversion to potential energy. These processes involve interactions of a vehicle with its environment and lead to the develpment of substantial forces. The structural response and gross motion of a rail vehicle are extensively interelated. The former is best suited to examinations using fiinite element analyses while the latter would typically be examined using a multibody dynamic simulation. Impact forces and inertial effects can be approximated by applying quasi-static forces onto finite element models while simplified stiffness representations can be implemented in multibody simulations to approximate the effects of structural impact. Some dynamic finite element analysis codes such as the DYNA/NIKE family, i.e. those capable of considering inertial effects and surface contact, are very useful in examining impact situations since they are capable of simulating both the gross motion and the local deformations of an appropriately constructed model.

Multibody dynamic simulation techniques used in conjunction with descriptions of actual derailments could provide a valuable means of predicting plausible rail vehicle impact loading conditions for use in subsequent detailed dynamic finite element analyses. This would facilitate superior estimation of cask impact velocities, attitudes and locations than those based solely upon the consist speed at the time of derailment and engineering judgment based upon general considerations of gross topological features in the vicinity of the railway right-of-way. It would be particularly useful for characterizing initial conditions for impacts between a representative rail cask and other vehicles in the consist.

The free body motion of rail vehicles during a derailment is thought to be sufficiently significant to warrant consideration because of the similarities between the masses and rotational inertias of the representative rail cask and other rail vehicles it may impact duing a pile-up. This implies that large forces are likely to be involved in a momentum transfer between impacting vehicles as they deflect past one another. The impact forces would build up rapidly to the maximum sustainable levels associated with the deformation of the structures involved at that instant in time while inducing only a relatively slow acceleration response of the vehicles when compared with the closing impact velocity. Moreover, the effective stiffness of the structures involved may increase after becoming sufficiently deformed due to contact between folds of deformed material thus increasing the influence of stronger underlying structural elements. The process of plastic deformation will be an important factor involved in removing energy, but it does not occur in isolation and will both influence and be influenced by changes in the relative motion of the impacting bodies. It should therefore be important to consider the extent, particular nature and time history of such energy removal during dynamic impact situations in addition to quasi-static estimates of a structure's maximum crush load capacity.

One limitation of these models is that they produce identical results for the same set of initial conditions and they are costly to run. What is desirable is a balance of the range of models — detail simulation of inter-vehicle forces and their influence on the motion of the vehicles involved; combined with probabilistic events occurring at various junctures in the derailment evolution. For example a simplified simulation model that assumes flat terrain could interface with an interrupt to a probabilistic model that allocates a probability of coupler failure or of cask detachment from its rail car at critical junctures in the derailment process. The results of the simulations could be used to calibrate the train consist aspects of a parametric risk model such as that of Saccomano's described above. The other route specific characteristics, such as speed and accident cause histories could be developed for the corridors of known interest.

5. **KEY ASSUMPTIONS IN THE CASK LOADING ANALYSIS**

The previous section has dealt with assumptions made in assessing the "frequency" of load events. This section deals with assumptions made in undertaking the analysis of the casks response to those load situations. The limitations of analytic tools in assessing derailment dynamics and forces will always lead to the development of simplified scenarios for analysis. The key question is—do any of the simplifying assumptions-and-representations lead to force predictions that are lower than those that might actually be encountered? In this section we review the loading assumptions to determine if all of the assumptions (both stated and inherent) were conservative ones leading to overestimation of actual forces. The section is divided in three parts dealing with: geometric simplifications, basis for dismissal of certain loads and the assumed magnitude of loads evaluated.

5.1 GEOMETRIC SIMPLIFICATIONS

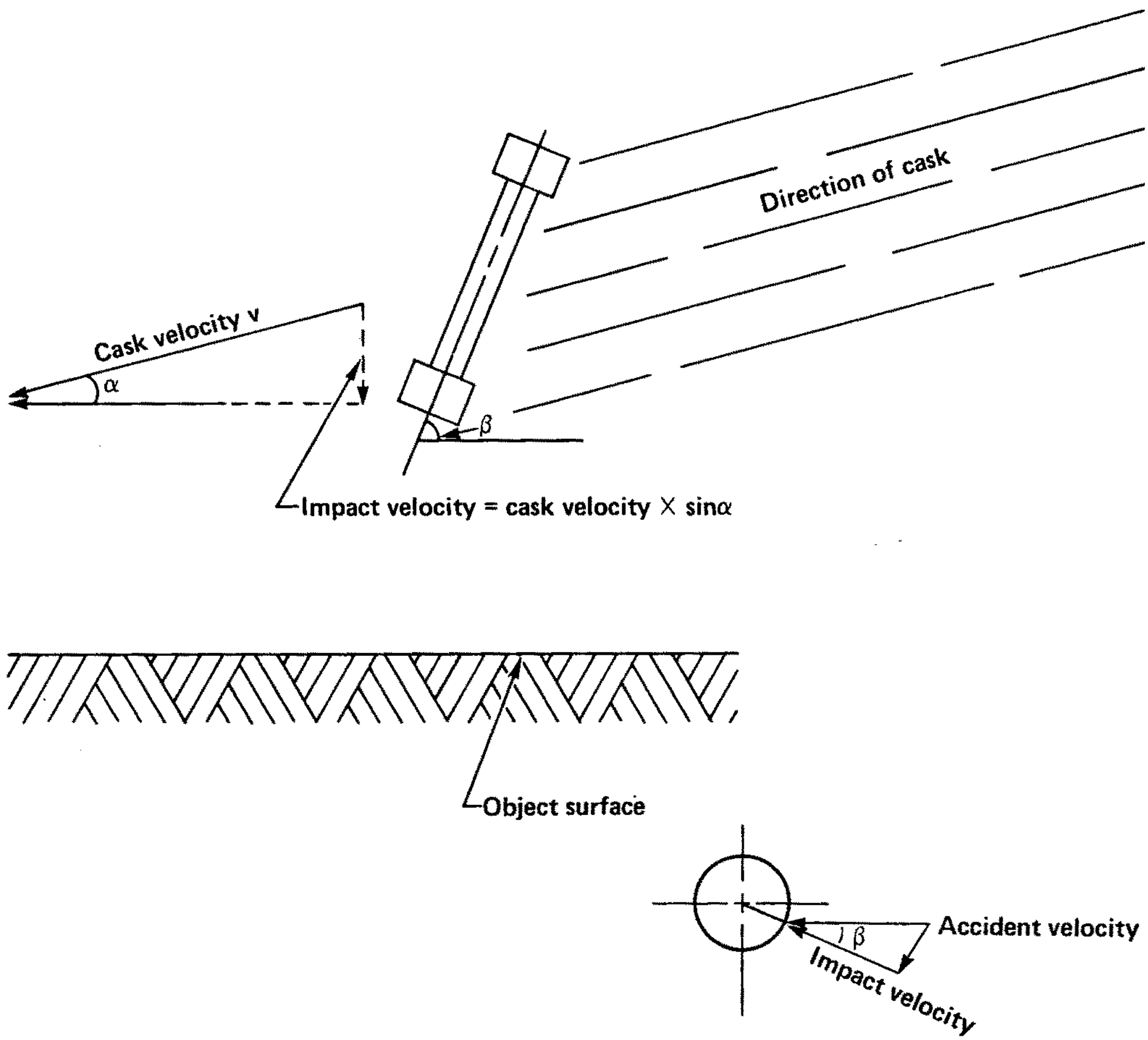
orientation geometry of object striking cask

Figure 12 illustrates the three parameters LLNL identified as important in assessing cask survivability of a rail accident. They are: the impact velocity (speed magnitude and angle with respect to the impact surface); cask orientation; and the hardness of the surface being impacted by the cask. The inset to the figure illustrates the geometry assumed for an object striking the cask.

5.1.1 Flat Surface Objects

We noted in Section 2 that the test specification of a flat surface raised the question of how the tests relate to uneven surfaces. LLNL also assumed that the majority of significant impacts were with flat body surfaces. The side impact situations largely involved flat surfaces that brought the impact limiters into play. Consideration of impacts with objects that are not flat raises the possibility of the object impacting the side of the cask in the region between its impact limiters or of an end impact not bringing into play the full energy absorbing area of the impact limiter. LLNL's approach is a convenient way to relate the analyses to the regulatory test conditions; however, it is not an accurate representation of surfaces encountered in derailments and collisions and leaves an important question unanswered.

The one area of analysis that offers some insight into the effect of uneven surfaces is that of other bodies impacting the cask. LLNL's analysis of a locomotive sill colliding with an unprotected cask raise further doubts of the adequacy of a flat surface regulatory test to conservatively represent non-flat surfaces arising in accident conditions. It must be noted that the locomotive sill is an uncommonly strong structural element. On the other hand as noted later in our review of the survivability analysis, this part of the LLNL analysis was performed on the basis of a fully distributed load across the length of the cask, was scaled from a 2-dimensional finite element analysis of a truck cask rather than assessed directly and assumed a structural strength that is in the elastic region of many railcar frames. Regardless of the assumptions, this load scenario is the only one that represents a realistic non-flat, yet deformable surface (as opposed to the regulatory 'unyielding' surface). A more detailed assessment of other types of surfaces under other speed and orientation scenarios should be evaluated.



orientation geometry of object striking cask

Figure 12 Three Impact Parameters Assessed (Source: Figure 6.3 of LLNL)

Several train accident scenarios involving casks striking ground surfaces adjacent to the railbed (8, 22 & 23) were assessed as minor based upon the assertion that the fall height would be less than 15 feet and the impact velocities would be less than 22 mph. It is stated (p. 6-23) that such impact velocities would only partially crush the cask's impact limiters and the footnote to the table indicates that the linear impact force would be less than 100,000 lb/foot. This would be true for the most optimistic case involving flat surfaces, however real ground surfaces are not necessarily flat. In the worst case, the exposed side of the cask could strike a hard object protruding from the ground such that a large impact load distributed over a small contact area develops before the impact limiters come into contact with the ground and begin to remove impact energy. A more reasonable scenario would fall somewhere between the extremes of a purely impact-limited fall onto a flat surface versus a purely concentrated impact load in which the impact limiters are not capable of removing any impact energy.

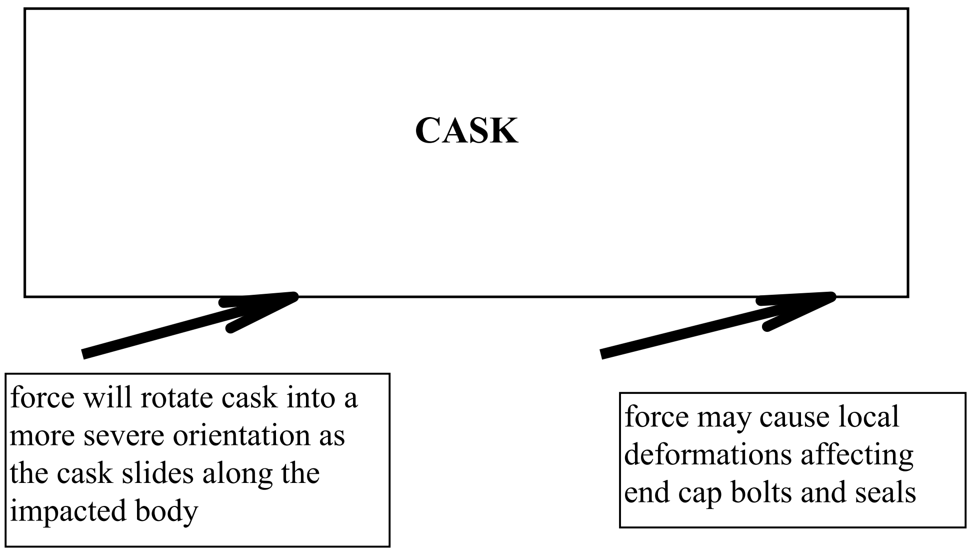
The importance of the impact limiters to impact survivability can be illustrated by way of some simple hand calculations. The cask design selected for analysis by LLNL has a force-deflection characteristic on end-loading such that force rises linearly from zero to 8,000,000 lb as the body is compressed from zero to 0.15 inches (LLNL Figure E-8). The cumulative energy absorbed in defelcting the body to 0.15 inches is the average force mutiplied times the deflection, which for this case, and converting inches to feet, absorbs 50,000 ft-lbs of energy. The 8,000,000 lb force creates about a 40 'g' acceleration for the cask body and is the threshold where LLNL predict the onset of damage (or non-survivability of the 30 foot drop test). This highlights the importance of the impact limiters to cask survivability. All precautions should be taken to ensure that they can not become dislodged in the dynamic interaction of a derailment.

The exposed sides of the cask (about 4 meters between impact limiters) are vulnerable to direct contact with many large objects. While the side deformation characteristic and long aspect ratio would mitigate against rapid development of forces, the resulting deformations are expected to be much larger than would result from a flat surface where the inpact limiters absorb impact energy.

5.1.2 Single Impacts / Impact Velocity Angle

It has been assumed by the LLNL analysts, and seems to be a generally accepted view amongst packaging designers and regulators, that impacts provide the most significant source of mechanical loading that a massive container, such as the representative rail cask design, is likely to encounter in a real accident. Moreover, the initial impact is generally felt to be of primary concern. This is presumably derived from a drop test scenario where most of the energy would be removed during the initial impact and therefore additional secondary impacts would only have very low energy content. Nonetheless, the IAEA does require consideration of secondary impacts. One example of a potentially significant secondary impact would be package "slap-down", where a long package is dropped obliquely such that it rotates about the initial impact region and contacts the target at a second impact point. This situation would develop for many of LLNL's glancing blow situations that they assess at minimal impact speeds. In a cask-impacting-other-objects scenario, the energy extracted is small for glancing blows. The 'slap-down' scenario would evolve from a vertical cask orientation in a largely horizontal speed impact with flat surfaces. In a derailment situation where many other vehicles are involved the probability of later impacts of higher magnitude goes beyond this subset. There is a high probability of later collision in all cases where little energy is extracted from the first impact. The other aspect of the glancing blow scenario is that the assessed forces associated with the impact are only valid when a flat surface is impacted. If an impact occurs with a non-flat surface near either end of the cask the consequences could be more severe. Figure 13 illustrates two shallow angle impact situations that could develop into more severe damage than a simple impact force related to the sin of the impacting angle. At the left end of the cask, the cask would be rotated into a more severe orientation, and at the right end of the cask, the impact limiter could be dislodged and/or the integrity of the end cap seals may be affected; particularly if the cask is not free to rotate (as may happen in a derailment pile up of cars/casks).

Figure 13 Illustration of Glancing Blows



5.2 CASK ORIENTATION

We considered the cask orientation assumptions to be conservative ones.[10] On the other hand the high strain level data points were not as clearly identified in the Appendices. For example, the speed selected for the 2% strain level was 45 mph and was based on a test including cab crush effects (LLNL Table E.9, pg. E-32). The actual strain for the data point equivalent to the other tests was 3.6 % (LLNL Table E.12, pg. E-38).

The other aspect of the orientation assumptions that was non-conservative was that the cask had no rotational inertias. If the broad range of angles are feasible, then a rotational velocity is also likely. The strains resulting from impacts would be different if one combines the possible contribution of rotational inertia with the linear momentum of the cask. For the low impact angles and intermediate orientation angles the rotational inertia contribution may be the dominant load. Since the rotation may be either mitigate or exacerbate the loads depending on the

[10] The characteristic selected in LLNL's Figure 5.1 to summarize the data bore little resemblance to the analytic data for intermediate angles between 90° and 0°. However, the intermediate angles had strains below that of the selected relationship.

direction, the overall result of its inclusion would be to disperse the results about the mean value their estimate represents. Half of the cases would experience a more severe load and half a less severe load. The net effect would be to increase the frequency of exceeding threshold strain levels above the mean value.

5.3 LOAD CHARACTERIZATION

A number of concentrated load scenarios have been identified by Eggers as being potentially critically significant with respect to the survivability of a typical package designed to carry type B and fissile material when subjected to severe railroad accident conditions. These include various load combinations applied in the vicinity of a cask's end closure, valve penetration and impact limiters. A summary of these scenarios have been extracted from that report and included here as Appendix A for convenient reference. Although the LLNL study has made use of information contained in that same report, the response of the representative rail cask to these significant loading conditions was not investigated by analysis.

Details of the end closure and seals were essentially ignored in the study. This approach was taken since the end enclosure structure is massive and it is assumed that the stress level and extent of deformation are small in this region of the cask. This assumption is probably valid for most impact cases; however, it is possible that side impacts near the end, but away from the impact limiter, could cause seal damage. In addition, consideration should be given to the closure bolt strength that is not discussed in the text of the report. One scenario that could lead to closure damage would be an end-on impact where the mass of the contents impact against the recessed end closure, thereby loading the bolts in tension.

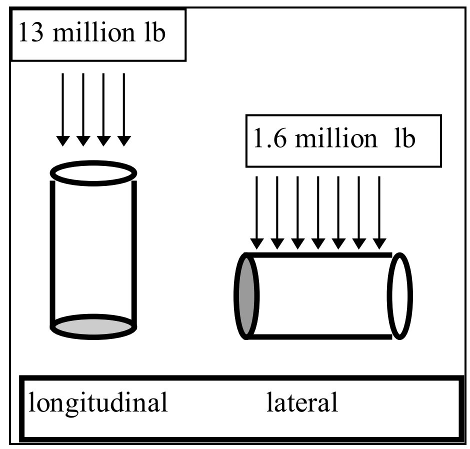
In a discussion of these basic design features the LLNL report suggests that the representative rail cask design need not include detailed representation and analysis of these features since it could be presumed that the impact limiters would provide adequate protection and that sufficient safety factors would be inherent in any real cask design. This is not intuitively obvious and is somewhat at odds with the critical loads identified by Eggers. Whether these scenarios could lead to damage and an increased probability of content release is uncertain, but cannot be ascertained from the LLNL study results or the level of detail provided in the end closure description.

As noted previously, the regulations require that the tests be applied to a package such that the resulting damage is maximized. The package designers would be required to demonstrate to the satisfaction of the appropriate regulatory body that the worst case had been considered. However, the extent to which the regulatory mechanical tests are capable of representing the severity of loadings similar to those identified by Eggers in a reasonably achievable rail accident has not been determined. Further, we have noted previously that there is no indication the impact limiters are designed to avoid becoming dislodged in a derailment situation.

5.4 MAGNITUDE OF LOADS

The primary focus of the dynamic impact analyses was on impact loads associated with a moving cask striking flat surfaces or stationary objects, although a much more limited treatment was given to situations where a moving object strikes the cask. Puncture and crush type loads were essentially dismissed as significant events without performing rigorous analyses because they occurred infrequently (on the order of 10 times less likely to occur) and were felt to be unlikely to cause damage due to the low energy content and "softness" of impacting objects when compared with the massive and hard cask structure.

The assessment of the representative rail cask's response to minor accidents revolved largely around its capability to resist static loads. Using an axi-symmetric 2-D finite element model of the representative rail cask, it was determined that 13 million pounds of longitudinal force would be required to initiate yielding within the inner stainless steel shell. Another 2-D finite element model was used to establish the 1.6 million pound lateral force capacity of the representative rail cask design. This would appear to represent the total static load, when applied as a constant 100,000 lb/foot along the entire length of the cask, required to achieve yielding within the inner stainless steel shell. Subsequent comparisons between the assumed accident scenario loading conditions and the cask's capabilities were then made in terms of the estimated total force and linear force that could develop in such an accident.



Classification of the minor accident scenarios was done through comparison of the cask's capability to withstand quasi-statically applied distributed loads. It was indicated, although no details or references were provided, that quasi-static methods were used to support the assertion that high velocity impact forces with automobiles and trucks could be bounded to a maximum value of 400,000 pounds. LLNL's summary table of quasi-static impact forces for various objects is duplicated here in Table 1.

Some calculations are outlined within the documentation as well as several references to reports of crash tests by the US DOT and the Sandia National Laboratory were offered in support of these values. While the gross magnitude of the impact loads established for the minor accidents cases do not appear to be significant with respect to the representative rail cask's overall crush load capacity, no analyses or discussion related to localized deformations are provided. It seems improbable, due to the high strength and ductility of the 304 stainless steel material, that breach of containment would result. Nonetheless, analytic proof would be desirable. In addition, the significance of localized deformations with respect to reductions in the thickness of gamma shielding material has not been established.

Object	Total Force (lbs)	Linear Force (lbs/ft)
Truck Cask		
Endwise	3.300,000	
Sidewise	1,600,000	100,000
Rail Cask		
Endwise	13,000,000	
Sidewise	1,600,000	100,000
Auto	50,000	<10,000
Truck Tractor	100,000	<17,000
Truck Trailer	450,000	<70,000
Train	2,000,000	>250.000
Motorcycle	20,000	<10,000
Bus	300,000	<50,000
Sound Wall	50,000	<50,000
4 X 4 Column	900,000	>225,000

Table 1 LLNL's Quasi-Static Force Evaluation for Impacted Objects

Source: LLNL Table E.7

Information is available that suggests the potential for large concentrated forces to develop during impacts with rail vehicles. A set of extremely severe railway accident environments has also been identified by Eggers for both mechanically and thermally applied loads. The mechanical loadings encompass long duration crushing of a cask, impacts between a stationary cask and a moving object and impacts between a moving cask and a moving or stationary object. The thermal loadings encompass concentrated torch loads, distributed loads, a cask engulfed in a fire and thermal isolation of the cask. A summary table of these loads has been extracted and reproduced in Appendix B for convenient reference.

These forces, as summarized in Table 2 below, represent the compressive forces required to produce unstable plastic deformation of the car's sill structure. The largest impact force defined by Eggers was 4.64 million pounds representing the magnitude of a quasi-statically applied force required to produce unstable plastic deformation of a 200 ton locomotive sill. It should be noted that the 40-50 ton car in the Table is obsolete and would not provide a conservative estimate of railcar strength. The relevant general purpose freight car types are 100 ton and 70 ton cars, and 120 ton cars are becoming more common. The 150 ton car shown in the Table is presumably representative of a cask transport car.

In a recent investigation of locomotive crashworthiness, a 200 ton locomotive frame was predicted by Arthur D. Little Inc, using finite element analyses, to generate about 3 million pounds of force at its protruding striker plate and 10 million pounds of force at the neutral axis of its underframe before it begins to collapse (Figure 14).[xvi]

Table 2 Eggers's Estimated Load Capacity of Selected Rail Vehicle Structures

Vehicle Type	Location	Maximum Force
40-50 Ton box car	coupler corner of car sill	900,000 lb 185,000 lb
150 Ton car	coupler corner of car sill	3,600,000 lb 1,300,000 lb
200 Ton locomotive	coupler	4,640,000 lb

Source: Eggers Table 22

A body that can impart 10 million lb force is capable of damaging LLNL's subject cask in either end or side impacts. The cask would not significantly deform on end impact, but the 10 million lb force is enough to impart an acceleration beyond the 40 g damage threshold.

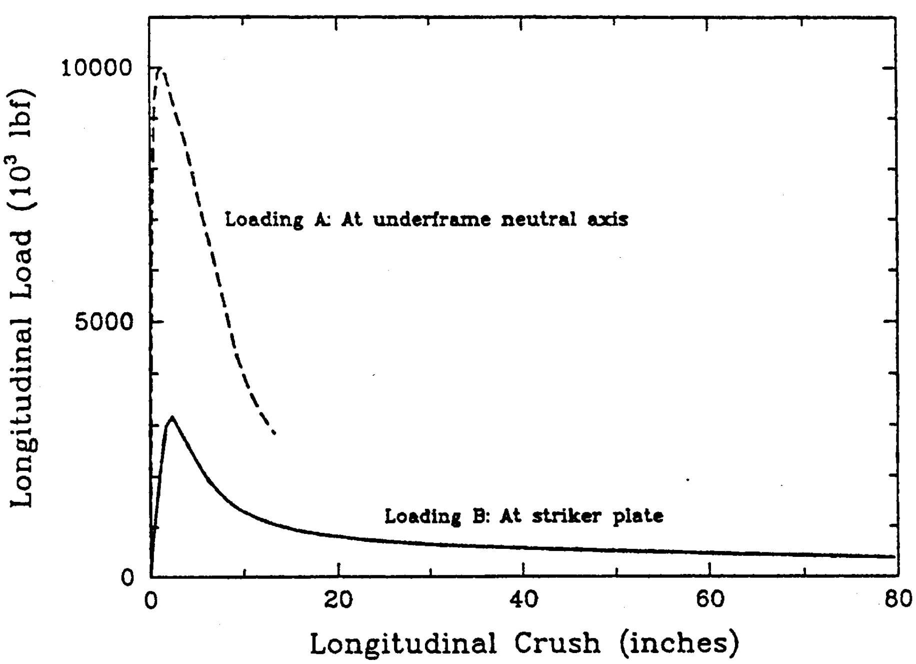


Figure 14 Load Crush Curves for 200 ton Locomotive

Source: Arthur D. Little, Locomotive Crashworthiness Research, DOT/FRA/ORD-95/08.1

Although no results of analyses equivalent to an IAEA pin drop test have been presented in the LLNL report, it is estimated that an impact force on the order of 10-15 g and localized strains in the order of 20% might be reasonably expected.[11] Using those figures the magnitude of the impact force would be in the 2 to 3 million pound range. The actual impact force and deformations would of course depend upon the stiffness characteristics and design details of the representative rail cask and a detailed analysis and/or testing would be required to more closely determine the actual values. Presumably, these investigations would be required to support a specific cask licensing application.

Impacts with rail couplers were identified as potentially significant mechanical loading events but unfortunately no data were provided in the report from which the magnitude of force development and the extent of localized cask damage during such an impact can be assessed. It is known, however, from data compiled by the Railway Progress Institute (RPI) and the AAR that coupler impacts are a significant factor in failures of tank cars during derailments. Analyses of accident data and the results of puncture tests have been used to establish a threshold for tank car puncture. Analytical work at the Sandia National Laboratory has developed a relationship from which puncture threshold velocities may be estimated for various thicknesses of mild steel.[12] This relationship can not be applied directly to the representative rail cask design since it was calibrated using a coefficient estimated from historical tank car accident data and will therefore be influenced by the materials and construction characteristics typical of tank cars.

Consideration of the historical tank car accident data could provide a particularly meaningful characterization of the incidence of, and conditions surrounding impacts of rail vehicles with energy content equivalent to or exceeding that of the regulatory pin drop test. This would provide a starting point for analyses in which the severity of the regulatory pin drop test could be directly compared with realistic accident conditions.

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[11] Personal communications with personnel at Ontario Hydro.

[12] III-42 of Dennis, et al. Sandia report # SAND77-0001

6. **CASK SURVIVABILITY ANALYSES**

6.1 MECHANICAL LOADING ANALYSES

The analyses reported in LLNL's document have been performed using a variety of techniques ranging from hand calculations to application of Finite Element Analysis codes. The philosophy of this analysis regime was to categorize the severity of a variety of accidents in terms of the capabilities of spent nuclear fuel transportation casks to withstand the corresponding loading environments. This was done using a very simplified model of a representative cask consisting of concentric inner and outer 304SS stainless steel shells that encase a layer of unbonded lead, used as the gamma shielding material.

The model was not detailed and did not include any realistic representation of the sealing and end-closure systems. Rather, a fundamental simplifying assumption was made that the extent of damage to the cask's primary functionality could be sufficiently characterized by the level of maximum effective plastic strain anywhere in the interior stainless steel shell. It was indicated that liberal use of conservative assumptions was made whenever simplification was necessary. The implication of this is that the analysts have attempted to mitigate any potential loss in analysis accuracy by recognizing that the response of the representative cask model would be inferior than any real cask likely to be used.

Three mechanical response regions were defined based on the maximum strain level observed in the inner shell material. The strain magnitude along and other characteristics assumed to correspond with each level are summarized below:

Strain Level 1 (S1):

- Defined as a fully elastic response region where the maximum strain at the inner shell does not exceed 0.2% (this corresponds with the yield point of the material as characteristically determined by a 0.2% offset strain).
- No permanent dimensional change, seal and bolts assumed to remain functional
- "little, if any, radiation release"
- Less than 40 g axial force on lead for all orientations
- No lead slump
- Fuel basket remains functional
- Up to 3% of fuel rods may release limited amounts of radioactive material into cavity
- Loads and releases are within regulatory design and release criteria

Strain Level 2 (S2):

- Defined as a moderate elastic-plastic response region in which the maximum strains fall between 0.2% and 2%.
- Small permanent dimensional changes
- Closure seal damage may result in limited radioactive material releases
- Limited lead slump resulting in increased radiation
- Up to 10% of fuel rods may release into cavity
- Loads nearly all absorbed by impact limiter
- Radiation hazards are "near regulatory limits"

Strain Level 3 (S3):

- Defined as a large plastic response region where the maximum strains fall between 2% and 30%.
- large distortions
- seal leakage likely
- lead slump likely
- all fuel rods release
- energy absorption by cask structure up to 8 times that of impact limiter
- radiological hazard outside regulatory limits but no solid release (except very small particles)

The S1 severity level corresponds to the strain to cause first yield as characterized by a 0.2% offset method. It is assumed that strains of this level will not cause significant damage and/or loss of radioactive material, a reasonable engineering assumption. The S2 level is assumed to cause local distortion and some damage to the fuel rods and seals with some loss of gaseous material. This treatment also seems reasonable, although the data for determining damage to fuel pellets (LLNL Figure 8.3) is not supported by reference in the report.

The S3 severity level represents gross plastic distortion of the cask such that seal loss and lead slumping occurs. The upper limit of 30% strain approaches the ductility of 304SS stainless steel. It is unclear what the treatment would be should this strain level be exceeded.

The choice of strain as characterizing the mechanical state of the cask seems reasonable since the impact event involves large plastic deformation. Stress or displacement are not representative of the 'state' due to the non-linear material response in this regime, as correctly argued in the report. Selection of strain alone as characterizing the response must be prefixed by a requirement of good material (and weld) ductility and toughness. The report argues that this is the case since casks are manufactured according to the ASME Boiler and Pressure Vessel Code that imposes strict material and welding requirements.

It should be noted however, that the fuel rod assembly itself is not addressed in any detail in the report. While strain may be an adequate surrogate for survivability of the containment cask, it may not apply to the contents. LLNL indicate that "prevention of criticality requirements is typically met by demonstrating that essentially no deformation occurs to the basket, the structure within the cask that holds the spent fuel." [LLNL pp. I-5][13] As we discuss later, their analysis predicts some very large deflections into the fuel basket area but which, by their analysis, exhibited low strains to the inner shell of the cask.

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[13] In a post draft discussion of this requirement, the LLNL authors indicated that this requirement is not a meaningful choice because the fuel rods are packaged in such a way as to provide the worst case arrangement and any deformation will lessen the hazard. They indicate that the 'no-deformation' requirement is tied to a desire to be able to remove the fuel basket from the transport container after an accident rather than a criticality requirement. Also, relevant is the level of effort required to substantiate the claims that the pre-packaged geometry is the worst case. As discussed on LLNL pp. 3-10, the prepackaged geometry must be shown to prevent criticality even in the event of water intrusion. If the 'no deformation' requirement can be met, then sub-criticality is known to be preserved without having to prove that it is also preserved with deformed or damaged fuel rods. Apparently, there is strong belief that deformation lessens the hazard but proving it would be a very expensive analytic exercise.

Impacts are characterized using three parameters: impact velocity, object hardness, and cask orientation. The numerical calculations are used to determine which impacts will lie in what category of strain severity; a two stage screening being used to categorize impacts. In the first stage, the inner wall strain is predicted using quasi-static calculations. Impacts that do not produce strains in excess of 0.2% are placed in the S1 category while those producing strains in excess of this level are re-analyzed using linear dynamic (for S2) or non-linear dynamic (for S3) calculations. The impacts are simulated for a range of impact conditions and interpolation based on impact force is used to fill in intermediate conditions.

6.1.1 Assumptions

The risk analysis approach adopted in the LLNL study requires consideration of a large number of accident scenarios and parameter variations within each scenario. Given the large range of possible permutations, a number of simplifying assumptions are made in order to make the impact calculations and risk analysis tractable. This section of the review examines the reasonableness and conservatism of various assumptions made in the survivability modeling portion of the LLNL study.

The overall methodology used in the execution of the structural analysis seems sound. There are numerous other examples where good judgment has been employed, lending confidence in the execution of the details of this study. For example, good engineering judgments are made in the selection of worst case material properties. Examples of this conservatism include:

> adoption of the ASME Pressure Vessel code values for material properties such as yield stress and hardening modulus, and;
> assumption of complete seal loss once strain severity level S2 or higher is reached.

However, as with the other areas of the study, a number of aspects of the structural analyses and the assumptions therein are not conservative ones, and should be re-examined if one is to be confident of the results. The areas of concern are dealt with in the following discussion.

6.1.1.1 Neutron Shield

Very little description of the neutron shield is provided except that it would likely be a water jacket surrounding the cask. The mass of this shield could be large and its potential effect on the mechanical response of the cask could be significant. In addition, even if the shield would not play an important role in the cask mechanical response, it may be important to model the damage and deformation of the shield since the shield plays a role in the thermal loading (as discussed in a later section). These concerns may not be relevant as AAR personnel indicate the current design does not incorporate this feature.

6.1.1.2 Penetration During Impact

The majority of the simulations in the LLNL study are limited to impacts with flat surfaces. Little consideration is given to impacts likely to cause penetration, the exceptions being an I-beam and a rail sill impacting the truck cask. The case of a locomotive sill impacting the rail cask was treated by factoring the truck cask results on the basis of relative responses of the truck and rail casks impacting a rigid surface. No consideration is given to impacts with surfaces containing hard protrusions that will tend to focus deformations. LLNL provide evidence of the capability of their DYNA-3D computer program to perform such assessments (benchmark example Figure H-3. in Appendix H provides a rather nice illustration of this effect). However, this type of detailed representation was not applied to the analysis of rail cask survivability. Their analysis of a locomotive sill impacting a truck cask goes part way towards such a case, but these calculations were two-dimensional plane strain so that the impact occurs along a 'line' rather than a 'point', thus distributing the impact forces over a larger area. We return to this issue later.

6.1.1.3 Fuel Rod/Basket Assembly

The assumption is made that the mass of the fuel rod and basket (support) assembly will have little effect on the mechanical response of the cask during impact. This assumption is difficult to assess since very few details are given concerning the truck and rail cask contents (e.g. basket geometry, strengths, total mass...). Earlier in the appendix (page E-28, second paragraph), the authors discuss a sensitivity study from which they assert that the mass of the contents was not important. This assertion is contradicted later in Appendix E (page E-89, second last paragraph) when the authors state that the mass of the rail cask contents were large relative to the mass of the cask.

In addition to adding mass and resulting inertial loads during impact, the contents of the cask may also add significant stiffness. This contribution will be particularly important for the side impacts during which the contents will tend to prop open the cask and will reduce the extent of ovalling seen in their response illustrations. The added stiffness would also be an important factor in determining the strains associated with penetration-type loads as depicted by the pin-drop test (penetration type loads were not assessed by LLNL for the rail cask).

6.1.1.4 Subcriticality

While the authors of this review are not qualified to address the issue of subcriticality, it is necessary to consider the assumptions made regarding the stability of the spacing between the fuel rods during impact. An assumption is made in the LLNL report that the fuel rods are supported in such a way as to prevent the rods from coming together, however, no details of these supports (baskets) are given. During side impact, the significant amount of ovalling predicted by LLNL models could lead to damage to the contents. It is also mentioned in the study that the rods are expected to buckle during an end-on impact. The large lateral deflections associated with buckling of these slender rods could also bring the rods in close proximity.[14]

6.1.1.5 Impact Orientation/Targets

Impact orientation is important and point loaded side impacts, as discussed in the previous section, are largely ignored in the study. The choice of end-on and side impacts as limiting cases for the detailed DYNA analyses was based largely on the IMPASC results that indicated the 0° and 90° cases to be critical. The IMPASC analyses are thought to be lacking in detail, however, and it is likely that oblique impacts on the cask corner may have an effect on seal integrity. Such analyses would require fully three-dimensional calculations.

The impact studies consider the cask impacting a target or being impacted at some initial impact velocity (or force). In the simulations, the casks are free to rebound and do not undergo subsequent impacts. For the case of rail cask shipments, it may also be necessary to consider impacts in which the cask is pinned in place during a rail pile-up and may have to absorb multiple impacts.

6.1.1.6 Choice of Representative Model

The selection of a lead gamma shield for the representative cask does seem to be the most conservative choice from the point of view of lowest strength and shielding loss due to lead slump. However, it is possible that the depleted uranium (DU) and steel-shielded casks should also be simulated since the associated impact limiters are stiffer than those of the candidate cask and the resultant internal stresses will be higher. Higher levels of damage to the seals, the closure bolts, and the contents could result, and may have an impact on the overall containment effectiveness.

6.1.2 Modeling Techniques

The predictions of the mechanical response of the casks to impact are based upon a series of numerical simulations utilizing three possible software programs: DYNA2D/3D, NIKE2D/3D, and IMPASC. The DYNA and NIKE codes are so-called "sister codes" that handle dynamic, large deformation analyses. DYNA uses explicit time integration and is suitable for short duration dynamic analyses while NIKE uses implicit time integration and is better suited for longer duration events such as structural dynamics, that do not involve stress wave propagation. As such, both of these codes are well suited to handle the impact analyses in question, although the DYNA codes are better able to handle the large deformations and contact conditions occurring during the impacts. The approach taken to use NIKE to screen out the elastic regime impacts and to use DYNA to model the higher energy elastic-plastic impacts seems consistent with the normal use of these codes.

[14] We reiterate the earlier note under this topic that the LLNL authors indicate that damage to the contents is not a concern to criticality and the 'no-deformation' criterion they cited in the report is a misnomer.

The most striking aspect of the numerical simulations is the use of rather coarse finite element meshes and only limited consideration of three-dimensional cases. The use of coarse meshes can lead to significant errors in the predicted strain distribution. DYNA is particularly prone to discretization errors due to its use of linear displacement interpolation elements that at best model constant strain regions. In order to avoid discretization errors, standard practice requires the use of large numbers of elements, particularly when attempting to model bending and/or stress concentrations. The meshes used in this study are viewed as being overly coarse, particularly since the authors are attempting to resolve strain levels of less than 0.2%. Use of such coarse meshes cannot be justified without supporting mesh convergence studies that have not been included as part of the LLNL report.[15]

The meshes employed only two elements through each of the inner and outer shells and four elements through the gamma shield (LLNL Figure E-15). When one considers that these components are not bonded and thus bend about their own neutral axes, the meshes cannot capture bending stresses. This error is of less concern for the end-on impact case for which bending stresses and strains will be small compared to the axial components. However, the same meshes were believed to have been used for the two-dimensional simulations of side impacts. [16] In side impacts bending is the predominant mode of deformation — leading to pipe ovalling (deformation of a circular section to an oval shape) as can be observed from examination of LLNL Figure E-22.

The IMPASC code is unknown to the authors of this review and very little information or description of this code is given in the LLNL report. The only descriptive narrative on IMPASC that could be gleaned from this report was that IMPASC was a "1-D beam element code" (page E-25, last paragraph.) The reference E-14 for IMPASC is an internal LLNL report that was not provided for this review. As such, concerns exist over the use of this code. In particular, 1-D beam formulations generally do not take into account any changes in cross-section such as ovalling. They also assume that plane sections remain plane during deformation that would not be the case for an oblique impact in which a corner is impacted, for example. The majority of the impacts between 0° and 90° are modeled with IMPASC and these results are suspect if the formulation is based on a 1-D beam element. An adequate theoretical description was not available for this review.

Limited verification of the IMPASC results were reported to have been performed by comparison of the IMPASC and DYNA2D simulations for the 0° and 90° impacts. The one benchmark comparison provided in the report (for 'end-impact' LLNL Table E-11) showed NIKE-2D predictions of g-forces about 30% higher than those of IMPASC, and did not show the strain predictions of IMPASC. The 0° side impact bench-marking was not reported on**.** There was an assessment with NIKE-2D for a cask without impact limiters that resulted in extensive ovalling deformation of the fuel rod chamber (see Figure 15) and attained a maximum strain of 7.2% for a 60 mph impact. The IMPASC side impact case at 60 mph was modeled with impact limiters on and resulted in a maximum strain of 0.235% (LLNL Table E.10). LLNL argued that the

[15] In post-draft discussion with the authors, they indicated that mesh convergence studies were undertaken but are no longer available.

[16] The authors indicated in post-draft discussions that this mesh was used in all the rail finite element analyses.

IMPASC results were conservative for the cases bench-marked and therefore DYNA simulations were not performed for intermediate angles of impact. The reporting of the bench-marking process does not clearly demonstrate that the results of the two models are similar or that the IMPASC model predictions are conservative. Also, keeping in mind that such impacts are three-dimensional in nature and therefore expensive computationally, it is still necessary to perform a selected number of impacts between these extremes in order to verify the IMPASC calculations.

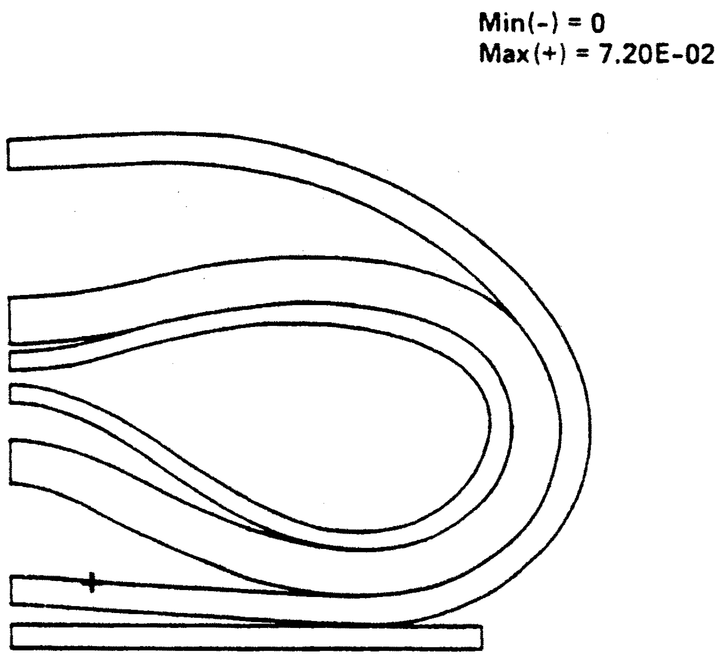

Figure 15 DYNA-2D Ovalling Predictions for 60 mph Side Impact

Source: LLNL Figure E-23

The use of the equivalent energy techniques to simplify the calculations involving impact of a deformable cask with a compliant surface seems reasonable and useful. Only one verification simulation was provided. It would be useful to examine the accuracy of this method for the entire range of soil and cask hardnesses studied.

6.1.3 Analysis Of Crush Loads

The crush capacity of the representative rail cask is reported to be 1.6 million pounds when distributed linearly along the cask at a rate of 100,000 pounds/foot. This evaluation was performed using a quasi-static (i.e. successively increasing statically applied loads) analysis of a 2-dimensional finite element model. The ultimate load capacity was assumed to be reached once the strain on the inner shell of the model reached the 0.2% offset strain generally considered to be equivalent to the onset of material yield. The choice of a 2-dimensional model for this analysis provides conservative results since all end-effects are necessarily ignored and the model is essentially an open-ended tube. The physical significance of this is that any additional strengthening associated with the presence of the ends of the cask are not included. It also appears that the model did not include the equivalent stiffness of the spent nuclear fuel bundles or MPC shell contained within the cask's cavity. The lack of any strengthening due to the presence of the spent nuclear fuel bundles would also provide a degree of conservatism. However, it should also be noted that; while being conservative from an overall deformation viewpoint, the presence of the spent fuel bundles and end caps would alter the stress and strain distributions and produce local strains higher than those produced without them.

The conclusion that the cask's crush capacity is not exceeded by the application of a 400,000 lb load distributed across the width of a 200-ton locomotive's seems supported. This assumed loading scenario differs in nature from the bounding crush loads defined by Eggers as either: a 100,000 lb load acting over a minimum area of 5.7 in^2 that represents half of an overturned 200 Ton locomotive's weight bearing on the cask's surface at the side of its sill; or a 100,000 lb load applied over an area of 5 in^2 representing half of the weight of an upright 200 Ton locomotive supported on a wheel contacting the cask's surface. This analysis does not characterize the level of localized damage, particularly in terms of loss of gamma shield thickness, that would be associated with these loads. It does demonstrate that the cask can withstand the application of distributed loads of at least 100,000 pounds/foot, but likely somewhat higher because of the conservatism inherent in the analysis. A much more useful measure when considering concentrated loading would be to evaluate the cask's response to various levels of surface pressure loads. This would be a more complex analysis as it would require the use of a 3-dimensional model. It would be possible with such a 3-D model to directly apply concentrated bounding crush loads such as those identified by Eggers.

6.1.4 Analyses Of Impact-Limited Loads

The severity of an impact in terms of damage sustained by the representative cask was then determined on the basis of the maximum level of strain observed anywhere in the inner stainless steel shell. For endwise impacts with flat unyielding surfaces, the predominant failure mode was characterized by strains induced by bulging of the inner and outer shells. This is caused when the unbonded layer of lead gamma shielding slumped towards the impacted end of the cask when subjected to the impact-limited inertial forces. The 2-D axi-symmetric model used for these analyses did not consider the mass of the payload. It was noted that sensitivity analyses were conducted using the 1-D beam element IMPASC code that established that inclusion of payload did not affect the maximum inner shell strain predictions. However, sufficient details were not provided or referenced that would allow further assessment of the particular analyses performed and the applicability of this assumption with respect to the full range of expected loading environments and failure modes of the cask.

For sidewise impacts of the representative rail cask with an unyielding surface, a two-dimensional (2-D) model was developed to perform a series of plane strain analyses using the DYNA 2-D code. Such an analysis can be viewed as estimating the response of a unit thickness of the cask's cross-section without considering end effects (i.e. the influence of material existing on either side of the model that would have a strengthening effect). The impetus of selecting a 2-

D model appears to have been to reduce the required computing effort. The simulated response of a 3-D representative truck cask model including impact limiters, but no contents, striking an unyielding surface was presented in support of the validity of using a 2-D representation. It was observed in that analysis that the centerline of the cask struck the unyielding surface at essentially the full impact velocity. The results of the 2-D analyses of the sidewise impacts between the representative rail cask and an unyielding surface revealed extensive ovalling (illustrated previously in Figure 15.

The primary failure mode of the cask, in terms of maximum plastic strain on the inner shell, was reported to be associated with the development of a plastic hinge as the cask walls folded in on themselves. However, it should be noted that the model did not consider the inertial (mass distribution) and stiffness properties of the spent fuel bundles contained within the cask and the observed response would not necessarily be representative of that if the contents were included. Certainly, the propensity of the package to deform would have been resisted by the existence of the fuel bundles and differences in the stress and strain distributions could be reasonably expected. Moreover, the inertial forces imparted on the inner shell in order to decelerate the fuel bundles appear to have been completely ignored. It is conceivable that these would have significant effects with respect to damage of the gamma shielding effectiveness. The authors of the report acknowledged the significance of the mass of contents that would account for approximately 26% of the total mass of a loaded representative rail cask. In contrast, a single fuel bundle carried in a loaded representative truck cask would account for only 6 % of the total mass.

6.1.5 Analysis Of Non-Impact-Limited Loads

There is a lack of detailed analyses of loads that are comparable to the IAEA drop II (pin-drop) test. In establishing that test, the IAEA has recognized that real impact surfaces are frequently not flat and puncture loads are likely to occur.[17] Moreover, it is possible for these loads to be applied in a manner such that impact-limiting devices or materials are completely circumvented, particularly for packages such as the selected representative rail cask that has long exposed sides that could be impacted during a derailment. In these types of impacts, energy can only be removed through deformation of the cask structure and that of the impacting object. The simplicity of the model used in these analyses also precludes examination of the significance of protrusions such as lifting lugs that may serve as sites of concentrated load application.

The LLNL report dismisses the significance of nearly all potential impacts between the representative rail cask and other rail vehicles that may occur during the course of a derailment pile-up without rigorous discussion and presentation of supporting results from detailed analyses. Rather, the categorization of accident scenarios into minor and severe mechanical loading occurrences appears to have been made by comparing the gross crush load capacity of the cask

17 IAEA Safety Series No. 7, para. E-627.3, p. 59.

with general estimates of the maximum impact loads and linear force distributions that real impacting objects are thought to be capable of developing.[18]

The only side impact loading condition on the representative rail cask pursued by analysis and reported on was intended to represent a locomotive sill impacting the side of the representative rail cask at its center line. However, this was achieved by scaling the response determined with a two-dimensional analysis of a similar truck cask impact. The model did not include a representation of the mass and stiffness properties for the spent fuel bundles that the cask would contain. Since the model was two-dimensional, contact between the sill and cask would have to be assumed to occur linearly along the entire length of the cask. It would be necessary to use a three-dimensional analysis to assess the cask's response to a concentrated load application.

The authors' use of the a distributed locomotive sill load in deference to a concentrated load was presumably tied to the results of their 3-dimensional finite element analysis of a 21 inch I-beam impact with the truck cask. This I-beam impact produced a 5% strain and 40,000 lb [19] impact force, compared with a 20% strain and 9 million lb force for the locomotive sill impact. This ratio of forces developed was one of the factors LLNL considered in eliminating puncture type loads from further analysis. However, we note that the locomotive sill impacts were conducted with a sill having an effective mass equal to that of a 200 ton locomotive. On the other hand, the I-beam only had the mass of a free body beam. If the I beam had been assumed to be connected to a locomotive (or if a coupler extension from a locomotive had been used) instead of a free body I beam, the impact force developed would have been much higher. We believe the concentrated loads developed by protruding elements from a locomotive, or associated with an overturned locomotive (i.e. a vertical sill orientation) would produce a worse load environment than the fully distributed load assumed in the analysis. We also believe the removal of puncture loads from consideration was based on an erroneous inherent assumption that puncture loads are only developed by light weight bodies.

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[18] The reporting of strengths is not consistent. In the appendices (Table E.7 on page E-26), the total quasi-static force to crush trains was reported to be 2,000,000 lb with a linear force distribution greater than 250,000 lb/foot while the main report (Table 6.4 on page 6-26) identifies locomotive and rail car superstructure force development to be less than 500,000 lb with a linear distribution less than 62,500 lb/foot. Impacts with sills and couplers were identified as possibly exceeding a linear force of 100,000 lb/foot. The sources for these force estimates were not clearly indicated.

[19] We believe the 40,000 lb may be a typographical error; 400,000 lb is more likely to be produced by a stand-alone I beam representative of one found in a rail vehicle.

6.2 THERMAL LOADING ANALYSIS

A thermal analysis should assess the effects of thermal loads on the following processes that may lead to radiological hazards:

- degradation of closure seal material;
- melting of lead shield;
- dimensional changes to structure;
- alloying of lead with SS structure, and;
- thermal isolation of the cask contents.

Temperature and strain can be used to quantify the above processes. Temperature can quantify the seal degradation, melting and alloying. However, strain is needed to quantify dimensional changes. While strain was the criterion of their mechanical loading analysis, temperature at the middle of the lead shield was selected as the single measure of the effects of thermal load. The following four states were defined on the basis of the magnitude of the lead temperature:

A	100° - 500° F	no significant damage -- water in neutron shield released
B	500° - 600° F	closure seals degrade
C	600° - 650° F	lead melts, deformation of inner cask wall
D	650° - 1050° F	fuel rods may burst

A one dimensional transient thermal analysis was performed to estimate the time required for the lead temperature to reach the various levels described above.[20]

6.2.1 Assumptions

In the analysis LLNL consider: fire duration, flame temperature, and fire location. Thermal strains are not assessed in the analysis. It is not obvious to the reader that this approach is conservative. Mechanical strains in combination with high temperatures could produce seal failures at lower thresholds. The thermal analysis also assumes that the worst case is an engulfing fire. Torch fires were not considered. Although less probable, large jetting fires are also possible and these could result in severe asymmetrical heat loads on the cask.[21] It was also assumed that the strain in the cask is not affected by the lead expansion at higher temperatures.

It is possible that the strains from asymmetrical heating are known to be low for the cask designs. We are not familiar enough with the cask design to assess the importance of these assumptions. The elimination of torch fires from the IAEA regulations was questioned earlier in Section 2. The LLNL report does not assess their influence nor does it offer reference for eliminating them from consideration. In fact the Eggers report that was one of LLNL's references cites torch fires

[20] A Finite Element code called TACO 2-D was used for the thermal modeling. This code was developed at LNL in 1978 and validated with benchmark cases. The report states that a 1-D model of the cask was used. The model calculates the transient thermal response of the multi-layered system to fire thermal radiation. TACO 2-D can account for lead melt effects.

[21] A torch fire has a concentrated flame close to the fuel origin. A jet fire is similar but involves a larger orifice and the flame is larger and further from the fuel source.

concentrated near seal locations as a load of concern. The flame temperature and the duration of torch fires can exceed that of a pool fire. While the total heat flux is lower and therefore the contents of the cask would not reach as high a temperature, the fact that it is concentrated at a small area can produce severe conditions for the area exposed to the torch. Thermal strains and high temperatures at the seals could be a concern. On the basis of the reports we have reviewed there is no reason to believe that such a load would not be of concern and may present local stresses and seal problems that would not develop with the regulatory pool fire.

The 1-D transient thermal model used, while adequate for predicting time to temperature for symmetrical heating cases, is not adequate for non-symmetrical heating. To assess the influence of torch fires a 3-D model would have to be used.

The thermal analysis made the following assumptions about the fire heat transfer:

- that the heat transfer is due to thermal radiation and convection is negligible;
- the regulatory conditions (i.e. a flame temperature the 1475° F in an engulfing fire scenario) was assumed to represent a 1700° F real fire condition;
- a flame emissivity of 0.9 was used.

LLNL's analysis assumes the type of fire and the test conditions specified by the regulations and look at sensitivities to temperature and duration departures from the regulatory pool fire. They adjust for a 'real' pool fire, as compared to an 'all engulfing' test fire condition by reducing heat flux by a factor of 0.78. Thus, a 1475° F engulfing fire scenario was assumed to represent 1700°F real fire (item 1 page 6-35 of LLNL). While there is logic in this adjustment, it fails to recognize that the IAEA justifies the use of lower flame temperatures and emmisivities on the basis that the all engulfing pool fire test conditions are worse than a typical pool fire. As noted before, these regulatory values may not be conservative with respect to severe railway accident conditions.

Another major assumption in the analysis is that the neutron shield water is lost but that the outer thin shield continues to act as a thermal barrier. It is not clear from the report how this relatively-thin shell that contains the water jacket is protected from mechanical damage, neither is it clear how and when the water leaks out. If it is possible for the thin outer shell to be torn off during an accident, then this would remove this thermal barrier and the heat flux to the cask would increase significantly. Increased heat flux would reduce the time necessary for the fire to damage the cask. Conversely, if the neutron shield water is not released, it could cause a pressure build up and possible explosion. While this possibility is not addressed in the report, it is possible that water release would have to be an element of the design in order to pass the regulatory test.

Another area of thermal analysis not addressed in the study was the internal heat generated by damaged fuel rods. The heat from normal fuel rod conditions is noted to be small compared to the external heat sources considered. However, the hazards associated with internal temperature rise from fuel rods following mechanical damage/concentration and/or cask insulation from being buried under debris was mentioned in other studies as a potential risk but was not addressed by LLNL. We are not familiar enough with this hazard to assess whether it is reasonable to disregard it. Again, justification for its exclusion should be pursued.

7. REVIEW OF VU/A'S ACCIDENT CHARACTERIZATION REPORT

7.1 OVERVIEW

As noted in the introduction to our report, the VU/A study attempts to characterize actual and hypothetical accidents within the thermal and mechanical severity matrix developed in the LLNL study. The LLNL matrix involves a mechanical loading axis and a thermal loading axis. The LLNL report contains estimated probability distributions for various parameters that are used to derive an overall probability of ending up in each of the cells in the matrix. VU/A use the parametric relationships predicted by LLNL for key accident conditions to "work backwards" from each cell to predict a possible set of initial circumstances that would attain the final consequences as represented by a specific cell in the matrix. They then looked for evidence of these parameters existing in published accident reports to illustrate the type of accident that could result in the severity level depicted by the cells in the matrix.

The review of accidents was apparently focused on the highway mode. There were no actual rail accidents attributed to any cells and each of the three severity regions above 'minor' had only one conceptual rail accident attributed to it.[22] There is no indication in the report of whether an attempt was made to find train accidents that would qualify for the various cells.

7.2 METHODOLOGY

As noted, both mechanical and thermal parameters were considered in the evaluation. The three parameters used for the mechanical loading have been illustrated previously in Figure 12; those for the thermal analysis are illustrated here in Figure 16.

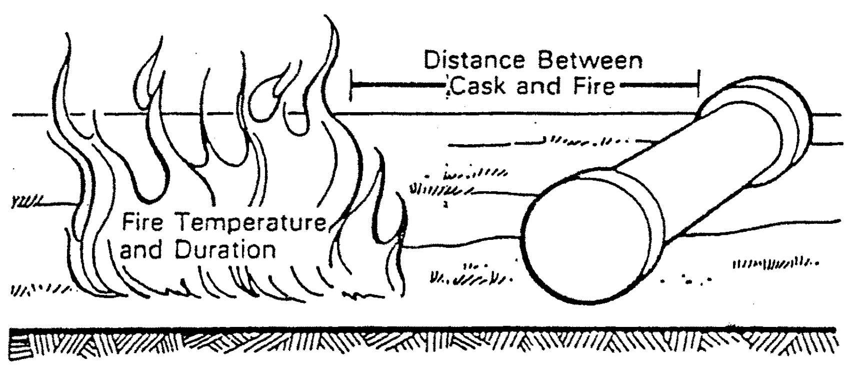

Figure 16 Thermal Response Factors

Source: VU/A Figure 3

LLNL had characterized the relationship of cask response to the following loading parameters:

mechanical factors:

- cask orientation angle (β in Figure 12);
- cask impact angle (α in Figure 12);

[22] A number of train-truck collisions were considered but from the viewpoint of a truck cask.

- impact surface hardness;
- impact speed.

thermal factors:

- distance from cask to fire;
- flame temperature;
- fire duration.

The parametric relationships estimated by LLNL were adopted by VU/A for all factors of interest. Our review of the report initially focused on the mechanical loading evaluation. A number of questions concerning data interpretation were raised in this review and we felt that a review of the thermal assessment was not justified. Thus, the remainder of this review deals only with the mechanical loading aspects of the study.

7.2.1 Mechanical Loading Analysis

VU/A attempt to predict the initial cask speed necessary to reach LLNL's three mechanical load thresholds assuming a specific combination of conditions exist for the other three parameters. This was accomplished via interpolation /extrapolation of data from two figures presented in the LLNL study. The two relevant plots are shown here in their original form. Our use of these figures introduces a third level of figure referencing. We present the figures in our own numerical order. The cross reference to the other two reports are:

our Figure 17 = VU/A Figure 4 = LLNL Figure 4.2
our Figure 18 = VU/A Figure 5 = LLNL Figure 5.1

Figure 17 is an extract of Figure 4.2 from the LLNL study, where it was described as a 'schematic' representation of a 'representative' cask in endwise impact with varying surface conditions. Figure 18 is an extract of Figure 5.1 from the LLNL study. It is described by LLNL as the strain-impact velocity relationship for the truck cask impacting an unyielding surface.

For the purposes of their study VU/A assume both plots to represent the same cask. This is a reasonable assumption, but if both were based on the truck cask there would be a small error in either the description of the case or in one of the data points. For the unyielding surface curve, the S2 and S3 level responses correspond to the data presented in Figure 18 for the 90° orientation; however, the S1 level response is closer to the 0° orientation that reaches this strain level at a lower speed than the 90° orientation. Since this plot is a schematic illustration presumably intended to illustrate the relative impact of going from unyielding to medium, and to soft impact surfaces, it may have been better used as the secondary parameter to infer hardness sensitivity to the 'actual' results for an unyielding surface presented in Figure 18. This is a relatively minor point but it does influence the derivation of impact speeds that VU/A presents in their Table 2 (shown in part here as Table 3). Our bigger concern is that we have not been able to derive the same numbers VU/A did.

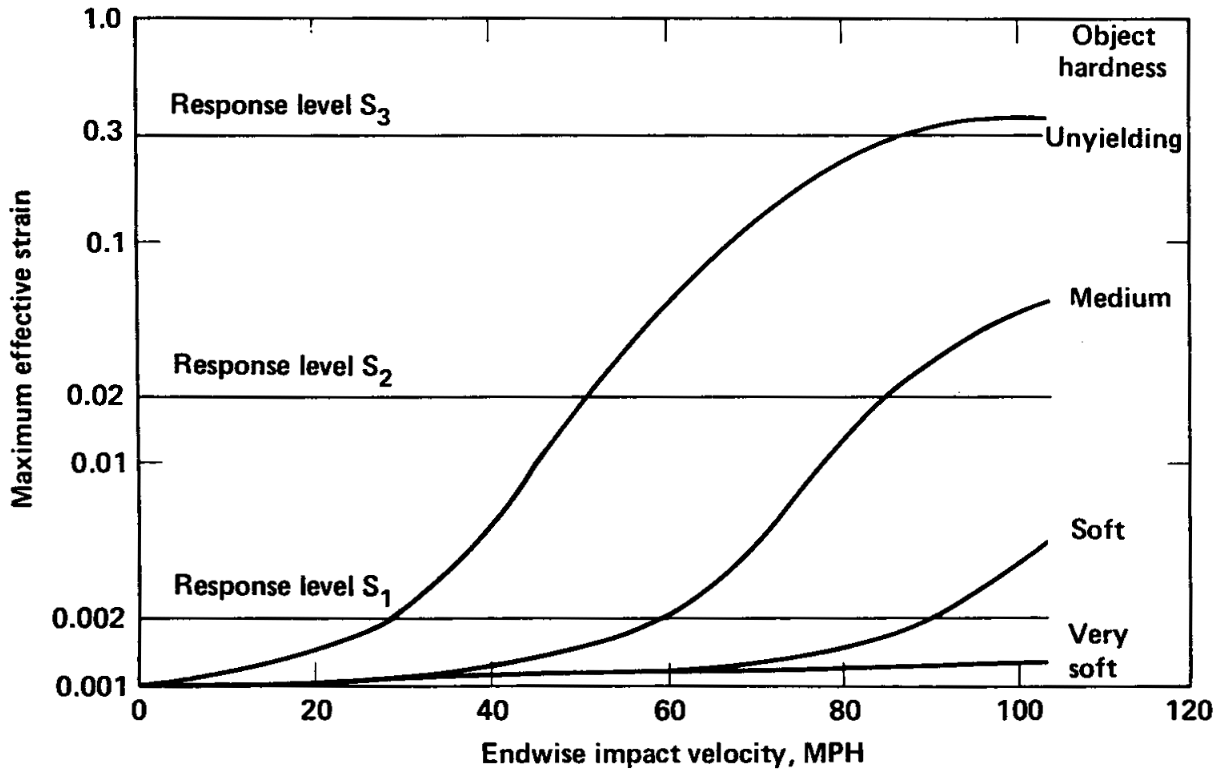

Figure 17 Structural Response by Surface Hardness and Impact Velocity

Source: LLNL Figure 4.2; VU/A Figure 4.

7.2.2 Data Interpretation Issues

The only explanation we can derive from the results VU/A presented in Table 2 of its report is that the authors misinterpreted the dashed lines in our Figure 18 as being the basis for scaling speeds. The following discussion refers to the case of unyielding object hardness shown in our Table 3 (extracts of VU/A Table 2 from pages 15 and 16). This case corresponds to the actual data presented in Figure 18. Conveniently, the figure has dashed vertical lines to most of the

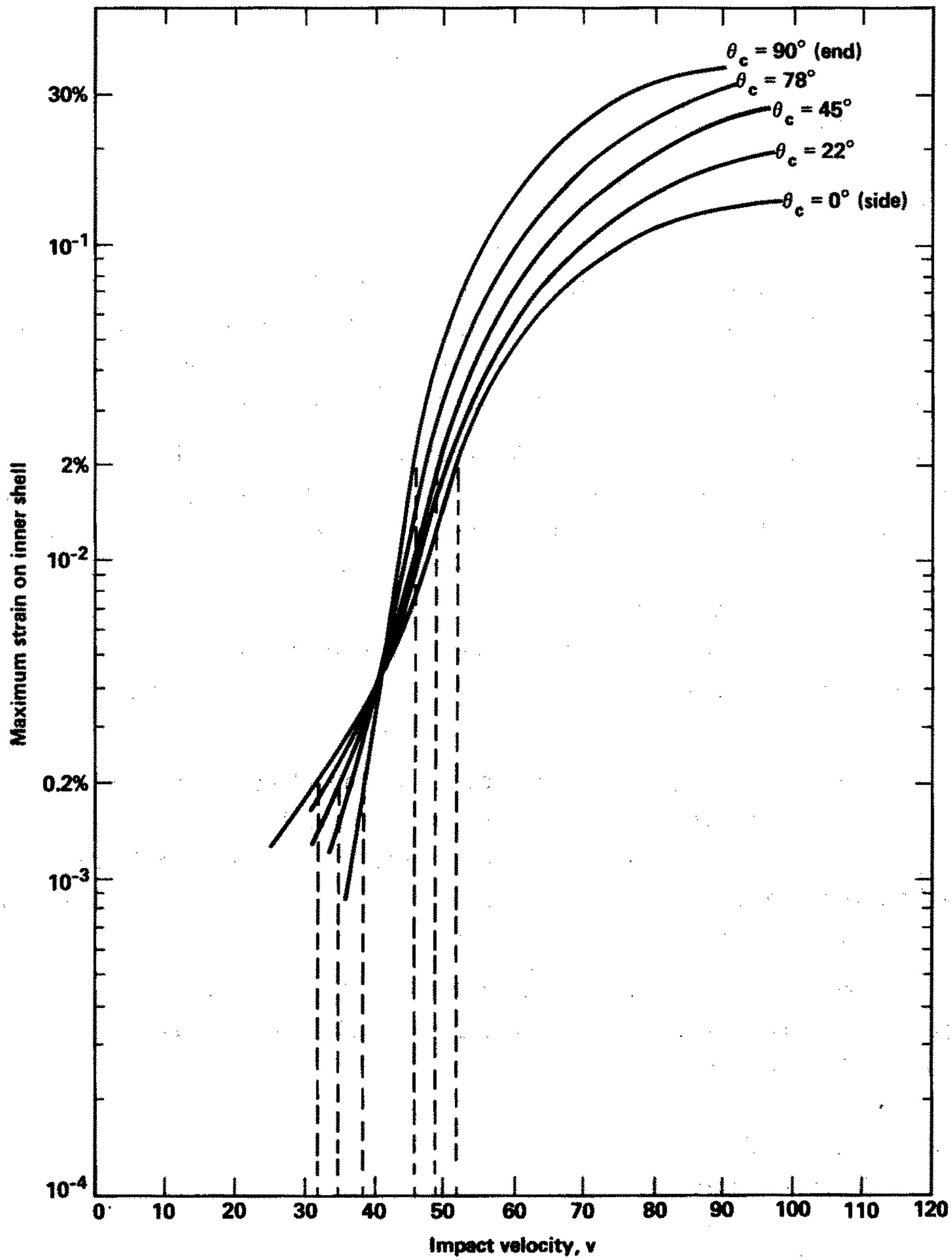

Figure 18 Structural Response by Cask Orientation and Impact Velocity for Truck Cask Impacting Unyielding Surface

Source: LLNL Figure 5.1; VU/A Figure 5

Response level S_1 → impact velocity of $\Theta = 90°$ is 29 mph

cask velocity = 29 mph/sin α

for $\alpha = 45°$

cask velocity = 41 mph → $\Theta = 45°$ → cask velocity = 41/1 = 41

$\Theta = 0°$ → cask velocity = 41/1 = 41

for $\alpha = 90°$

cask velocity = 29 mph → $\Theta = 45°$ → cask velocity = 29/2.38 = 12

$\Theta = 0°$ → cask velocity = 29/3.5 = 8

Response level S_2 → impact velocity of $\Theta = 90°$ is 50 mph

cask velocity = 50 mph/sin α

for $\alpha = 45°$

cask velocity = 71 mph → $\Theta = 45°$ → cask velocity = 71/0.5 = 142

$\Theta = 0°$ → cask velocity = 71/0.333 = 243 ← notreasonable

for $\alpha = 90°$

cask velocity = 50 mph → $\Theta = 45°$ → cask velocity = 50/0.5 = 100

$\Theta = 0°$ → cask velocity = 50/0.333 = 150

Response level S_3 → impact velocity of $\Theta = 90°$ is 87 mph

cask velocity = 87/sin α

for $\alpha = 45°$

cask velocity = 123 mph → $\Theta = 45°$ → cask velocity = 123/0.5 = 246 ← not reasonable

for $\alpha = 90°$

cask velocity = 87 mph → $\Theta = 45°$ → cask velocity = 87/0.5 = 174 ← not reasonable

$\Theta = 0°$ → cask velocity = 87/0.333 = 261 ← not reasonable

Table 3 Extracts of Unyielding Surface Case from VU/A's Table 2

Source VU/A, Table 2

points of interest. A rudimentary comparison of the data points in Figure 18 with the equivalent data points calculated by VU/A in their Table 2 highlights the problem. From LLNL's data in Figure 18, the impact speed at which a cask at a zero degree orientation angle (i.e. the line designated $\Theta_c = 0°$ (side)) reaches the strain level of 2% is shown by the farthest right vertical dashed line to be 52 mph. The equivalent point derived by VU/A as shown in Table 3 is response level S2, with velocity angle $\alpha = 90°$, and $\Theta_c = 0°$ (see the bottom of the second box). VU/A's indirect calculation of the speed for this point (that was already directly plotted in the LLNL report as 52 mph in Figure 18) is seen in Table 3 to be 150 mph.

The speed of this one situation has been overestimated by almost 300%. In trying to determine the basis of VU/A's estimates we identified three separate areas of significant difference of interpretation of the LLNL data presented in Figure 18. Our interpretation of the two LLNL figures and our assessment of the basis of VU/A's misinterpretation are discussed below for the 'Unyielding Object Hardness' cases depicted in Table 3. We reiterate that these cases represent the surface condition of the regulatory drop test.

Level S1. (first box of Table 3)

The response level S1 for 90° orientation is identified by VU/A as 29 mph. This point can be obtained from Figure 17 where the 'unyielding surface' curve crosses the 'response level S1' threshold. As already noted, the actual data point in Figure 18 is at 38 mph. If it were in fact 29 mph, the cask would not pass the regulatory drop test. This inconsistency in LLNL's original charts may have contributed to VU/A's data interpretation problems. In order to directly relate to the VU/A numbers, we continue to refer to the 29 mph data point in the following discussion, but caution that it is an erroneous number to begin with.

case 1.1 $\alpha = 45°$:

The orientation effect can be seen from Figure 18 to be insensitive at impact speeds of 41 mph. This must be the basis of their divisor of 1.0 used to calculate cask velocity. However, the horizontal axis of Figure 18 is "impact speed" not cask speed. It is the component of the cask's velocity vector perpendicular to the impact surface (see the velocity vector illustration in Figure 12) that is relevant in locating a point on the strain response curves of Figure 18. When the cask is traveling at 41 mph and at a speed vector of 45° to the impact surface, the ***impact speed*** is still 29 mph. It remains the reference point on the horizontal axis of Figure 18. Thus, we would choose the same divisor for a single impact speed regardless of the value of α that produces different cask speeds.

Our choice of divisors is also much different from VU/A's as better illustrated in the following cases where the divisor is not = 1.0.

case 1.2 $\alpha = 90°$

VU/A uses a divisor of 2.38 to calculate the cask velocity for the 45° orientation. There is no indication of the source of the 2.38 divisor. From Figure 18 we would identify the impact speed where the 45° orientation curve crosses the 0.2% strain threshold as 35 mph (highlighted by the second vertical dashed line on the Figure). This relates to a divisor of 38/35 = 1.086.

VU/A uses a divisor of 3.5 for the 0° orientation. Again we can not identify the source of the divisor. From Figure 18 we would identify the 0° case as 32 mph (the first vertical dashed line in Figure 18) that relates to a divisor of 38/32 = 1.188.

One possible explanation for VU/A's divisors is that they selected divisors from the vertical axis. If one extrapolates the lower speed region of the orientation curves it may be possible to obtain the ratios VU/A have used from the ratio of strains (plotted on a log scale) for a selected impact speed. For the S2 and S3 level cases discussed below VU/A applied the same divisor for each of the two impact velocities assessed. For 45° they used a 0.5 divisor and for 90° they used a 0.33 divisor. Again, the only source we could infer for these divisors was the ratios of strains for a fixed speed rather than the ratio of speeds for a fixed strain. However, it is not clear to us why they would derive speed ratios for a specified strain level by deriving strain ratios for a specified speed. Our interpretation of the data (and of VU/A's intended purpose) is that it is relative speeds for a fixed strain level that is of interest.

Level S2. (Box 2 in Table 3)

If one considers the S2 strain level cases (i.e. 50 mph impact velocity obtained from **Figure 17**), VU/A calculates the 45° orientation as 71/0.5 = 142 mph cask speed. From Figure 18 we would identify the 45° case in relation to a 90° impact speed of 50 mph as follows:

the actual 90° speed is 46 mph (first vertical dashed line from the 2% strain level) and the actual 45° speed is 49 mph (the second vertical dashed line from 2% strain level) which relates to a divisor of 46/49 = 0.9184. Similarly, for 0° orientation the speed is 52 mph giving a divisor of 46/52 = 0.885. If applied to their 50 mph case rather than the actual 46 mph case the results would be:

for α = 45°;

for Θ = 45°; cask speed = 50/ sin 45° /0.9184 = 77 mph. (not 142 mph)
for Θ = 0°; cask speed = 50/ sin 45° /0.885 = 79.9 mph (not their 243 mph)

for α = 90°;

for Θ = 45°; cask speed = 50 / 0.9184 = 54.4 mph. (not 100 mph)
for Θ = 0°; cask speed = 50 / 0.885 = 56.5 mph (not their 150 mph)

Level S3 (Box 3 in Table 3)

For the S3 level it is not obvious where one would get a divisor from Figure 18. If one extrapolates the curves for 45° and 0° one would anticipate much different divisors than those obtained at 50 mph. One could infer from Figure 18 that the 45° and 0° cases would require unreasonably high cask speeds at any orientation other than 90°.

7.3 CONCLUSIONS ON VU/A REPORT

To summarize, in our assessment VU/A have:

- scaled velocity ratios from the strain axis rather than the velocity axis;
- used cask velocity incorrectly as impact velocity;
- used speed rather than strain as the basis to relate the effects of impact surface hardness.

VU/A's development of estimates takes a circular path by choosing Figure 17 as the main reference and using Figure 18 to derive other points. In fact, their case of "Unyielding Object Hardness" is what Figure 18 is presenting. The other cases in their Table 2 (Soft and Medium) can be derived from Figure 17 by applying the speed relationships of Figure 18. We have done this and Figure 19 provides a comparison for Level S1 strains of their calculated cask speeds with our calculations.

case #	hardness	α	Θ
1	unyielding	45	45
2			0
3		90	45
4			0
5	medium	45	45
6			0
7		90	45
8			0
9	soft	45	45
10			0
11		90	45
12			0

Table 4 Case legend for S1 Strain Level shown in Figure 19

7.3.1 Methodology

Post accident analysis may result in an adequate characterization of thermal loads; the location and duration and type of fuel are all reasonably well described in accident reports. However, as noted previously, derailment mechanics is poorly understood and difficult to determine from post accident descriptions. It is not a valid method of characterizing the majority of structural loads developed in railway accidents.

7.3.2 Data Usage

In reviewing their treatment of the mechanical loading factors, we have come to the conclusion that VU/A misinterpreted the base data presented in LLNL's report. On the basis of the mechanical assessment, we did not pursue an assessment of the thermal analysis.

7.3.3 Overall

We conclude that VU/A's allocation of accidents to the structural response cells in the matrix has little meaning. In most cases they significantly overestimated the speed necessary to meet the loading thresholds for the matrix. On the other hand, they significantly underestimate speeds for the unyielding surface case, which represents the regulatory test surface. VU/A's derived speeds for the unyielding surface imply that the cask would not pass the regulatory drop test—an obvious misinterpretation of LLNL's data.

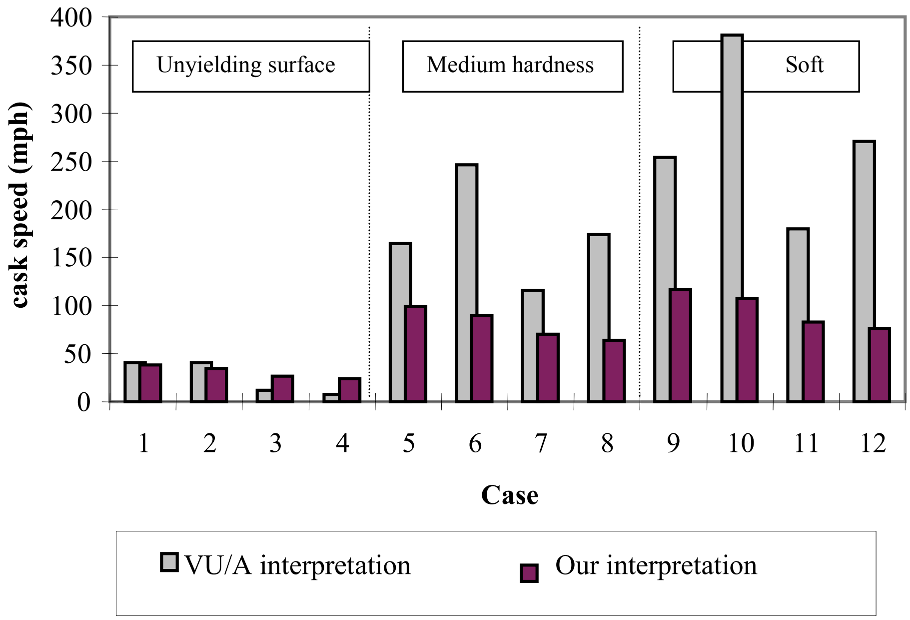

Figure 19 Cask Speeds to Attain LLNL's S1 Strain Level (Interpreted from LLNL Data)

As noted earlier, no actual rail accidents were cited in any of the severity cells. A review of newspaper articles would have identified the Chase MD or the Hinton AB collisions as high profile accidents that involved impact speeds of over 100 mph between freight and passenger trains. The fact that passenger trains (that presumably have levels of safety attention similar to that a nuclear cask train would be subjected to) were involved in both accidents highlights the risk of exposure to relatively high energy collisions. We did not pursue the analysis to determine if either of these or any other accidents should have be allocated to either 'severe' or 'very severe' (corresponding to LLNL's 2% strain and 30% strain criteria) severity levels. However, we had expected to see reference to such accidents in a report with VU/A's stated objective.

In our review of the VU/A report we have pointed out in detail what we believe to be errors in interpreting the figures from LLNL's report. To illustrate the errors we have derived cask speeds from LLNL's data using what we believe to be the proper interpretation. In doing so, we are not implying that our revised cask speeds are relevant to the VU/A's objective of characterizing real accidents. The overall approach must be viewed as an academic exercise in that it only considers the stiffness of the impact surface as the difference between real accident conditions and the regulatory test conditions. As noted in our assessment of LLNL's original report, there are other more important differences that need to be considered. The type of analysis undertaken by VU/A simply indicates the type of response one could expect if regulatory drop test number 1 were conducted on softer surfaces. Thus, we do not recommend either revisiting, or further pursuing this particular approach taken by VU/A in characterizing mechanical loading events in real accident situations.

8. RELEVANT FACTORS IN THE RAILROAD OPERATING ENVIRONMENT

To establish an effective operating practice, one needs to accurately define the threshold of cask survivability. As things exist today, the only guidance the AAR has in this endeavor is the interpretation of NRC test specifications for casks that indicate they must withstand a 30 mph impact effectively undamaged in order to be licensed. In our review of the regulatory tests, we identified a number of concerns with respect to the ability of the tests to adequately reflect the loading situations that may develop in a serious train accident. It is not clear to us that the tests insure that a cask could survive some loading situations. We looked to the LLNL and VU/A analyses of real accident situations to see if these concerns were addressed. However, most of the loading situations we expressed concern about were dismissed in the LLNL study without analysis and the VU/A study was completely derived from the previous LLNL study. We believe some of the issues (such as impact limiter retention, concentrated loads and dynamic crush loads) need to be resolved.

There is an incentive to develop regulatory tests for casks that guarantee survival of the types of forces expected in real train accidents. However, there is no evidence in the reports reviewed in this assignment that the existing tests achieve this. We reiterate, this is not to say it is not the case—a thorough analysis may end up concluding that train accidents are survivable by a cask licensed under the present test program. We note that, if the cask can be demonstrated to survive all but a specific kind of loading situation at a certain speed, it may be possible to address the identified hazards through other less costly methods. For example, thermal exposure can be fairly easily addressed with car-placement if survival of all mechanical loads could be demonstrated.

The rail industry's goal is to transport SNF in such a way that cask integrity is insured in the railroad operating environment while allowing timetable speeds without restrictions on meets or passes. Meeting the industry's goal requires the consideration of two factors, *frequency* and *severity* of accidents. It believes that a dedicated cask/car/train system addresses both of these factors and is the best method of meeting its goal. The *frequency* relationship is borne out by the historical relationship that the use of dedicated trains lowers the probability of being involved in an accident. This is because dedicated equipment can be subjected to inspection and maintenance standards beyond that economically justified for the bulk of lesser-risk freight movements. It also makes it feasible to consider special car-design features that will mitigate the forces to be developed in the event of an accident.

The amount of handling required for dedicated trains is substantially less than for regular trains, an important safety advantage. The more a car has to be handled, the greater the risk of an accident, even though the probability of an accident occurring in any event is small. If SNF cars were placed in regular trains, they would have to be "switched" in and out of trains at rail yards. Furthermore, if regular train service were used for SNF shipments, the switching of rail cars in and out of the trains would take time. Minimizing the amount of time SNF shipments are in transportation reduces the risk.

Dedicated trains would allow the use of premium equipment to be used for SNF shipments. For example if dedicated trains were used, the trains could be equipped with electronically-controlled pneumatic bakes, a recent industry innovation that can only be utilized where all cars in a train are equipped with these brakes.[23] Also, if dedicated trains were utilized, the NRC could require that all the rail cars in trains transporting SNF have premium suspensions. Premium suspensions reduce lateral wheel forces and vertical dynamic impact forces, which can result in derailments.[xvii]

Shorter trains facilitate monitoring by escorts. While a train-size limit could be imposed on any train as a practical matter implementation of a train size requirement would be readily achieved by the use of dedicated trains.

Dedicated trains would make it easier to make up trains in a way to minimize potential for train handling problems and hence the potential for derailments. Car placement can also influence the frequency of exposure to extreme heat sources. Many of the fires that do occur in derailments, originate with locomotive fuel tanks, so buffer cars at the front end would mitigate this. Similarly, fires originating with flammable liquids may be addressed through car-placement (to the extent that they are not placed in the same train). It is our understanding (although not confirmed) that UK car-placement restrictions prohibit any flammable or explosive carrying cars in the same consist as nuclear casks. These measures would also reduce the frequency of exposure to explosions. Even though the frequency of explosions is small, it may be more cost effective to take mitigating action by using dedicated trains or restricting the cars that can be placed in a train transporting SNF rather than incur the expenses of designing a cask to survive one. A risk assessment of the tradeoffs must recognize that exposure to such hazards would still exist from the possibility of adjacent train accidents in yards or at sidings.

No dedicated train design can totally eliminate the risk of accidents. Passenger equipment is an example of a dedicated train receiving preferred maintenance and design attention and yet there are still passenger train accidents; and as pointed out in the previous section, some very severe ones. Thus, the second factor incorporated into the industry's goal addresses survivability in the event of an accident. Dedicated trains could be designed to minimize the potential for post-derailment collisions between cars through use of special equipment. Shelf couplers (or possibly existing tight-lock passenger-car coupler designs) should be considered to reduce the probability of separation during a derailment. If all cars remain coupled during a derailment the chances of significant impacts between vehicles in the train is much reduced. Similarly, if side-sill bumpers or other measures are introduced to resist jackknifing in derailment situations, the chances of dislodging impact limiters and experiencing side impacts of the casks will be reduced. If the train operation/design prevents jackknifing orientations during derailment/collisions and/or if car design can incorporate protection of exposed areas of the cask, it may be better to keep the cask attached as long as possible to its protective transport vehicle than to let it break free.

[23] ECP brakes have shorter stopping distances than pneumatic brakes -- up to 70 percent shorter. ECP brakes are also more reliable, reduce slack action, improve fuel economy, and result in less wear and tear on wheels. Furthermore, the electronics used for ECP brakes permit constant monitoring by the train crew of the performance and condition of the braking system. *See* J. Lundgren, "ECP for Heavy Freight Service: Train Control and Monitoring for the 21st Century" (Transportation Technology Center, Inc. 1999).

In a configuration where cask cars are separated by specially designed buffer cars, the railcar structures it contacts will be of a lower strength. Further analysis of the level of puncture and dynamic crush loads that a cask can survive may indicate that some subset of existing car designs may be considered as suitable buffer cars and that their use as such may be accomplished by car-placement. An evaluation of the suitability of non-dedicated buffer cars would have to recognize the tradeoffs in train handling and car design / maintenance which increase the probability of experiencing a derailment with non-dedicated cars.

A dedicated train, without buffer cars puts more emphasis on the role of speed in the severity of impacts that will occur in an accident. But even in this area the relationships are not straight-forward. For collisions, buffer cars may be more effective in avoiding impacts than speed reductions are in mitigating their severity. Derailment mechanics are such that it is the interaction of cars and relative speeds and orientations among the cars that are important. These relationships are not well understood. Tank car puncture relationships to derailing train speed indicate that they can happen at very low train speeds and that a plateau develops as speed increases. The cask loading analyses performed by LLNL does not permit one to assess what this relationship may look like for casks.

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[xvii] D. Li and L. Smith, "Dynamic Vehicle/Track Testing on the Heavy Tonnage Loop" (Transportation Technology Center, Inc. 1999).

APPENDIX A

EGGERS'S ACCIDENT SCENARIOS

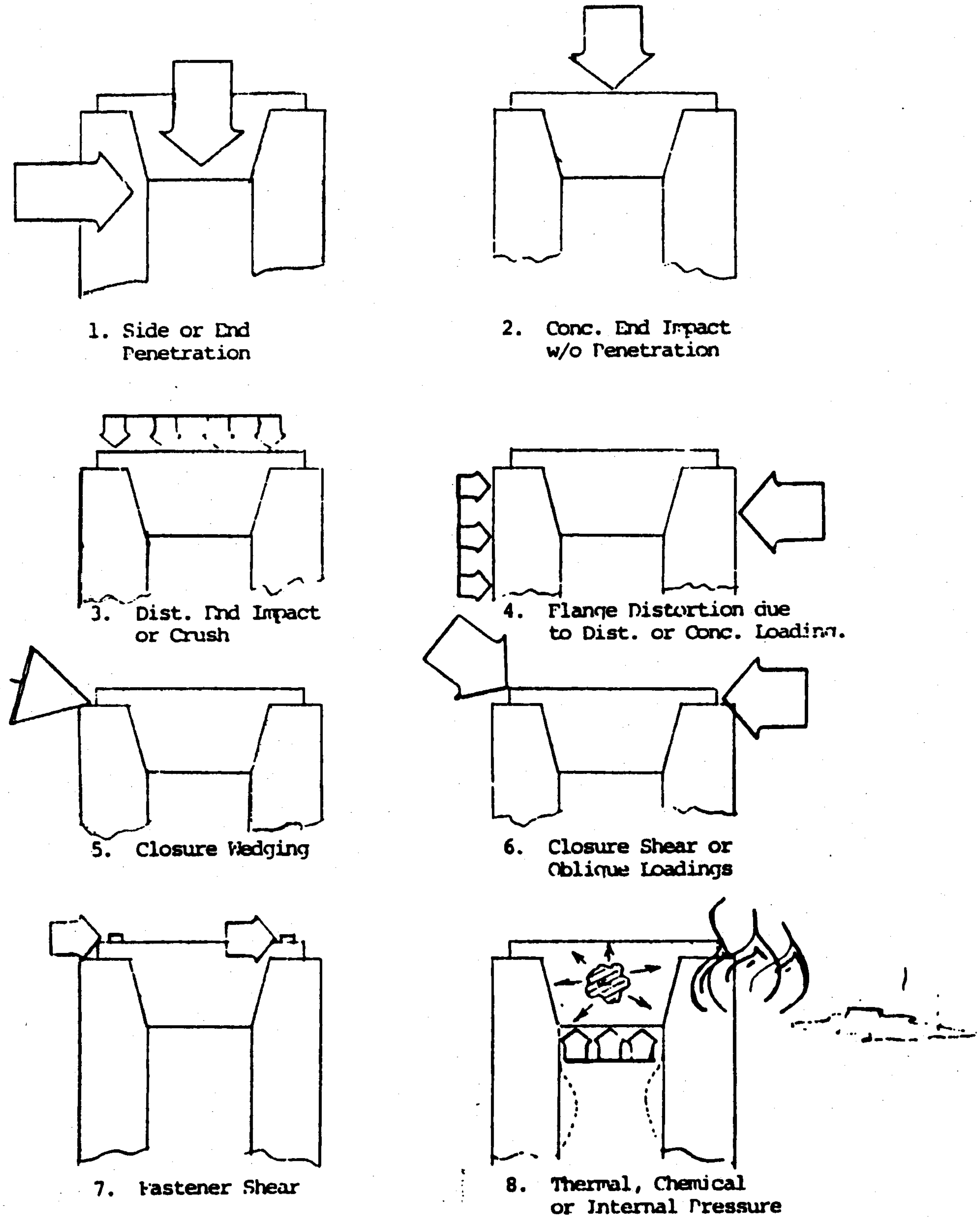

FIGURE 12. INFLUENCE OF END CLOSURE DESIGN ON POSSIBLE MODES OF INTERACTION WITH ACCIDENT ENVIRONMENT

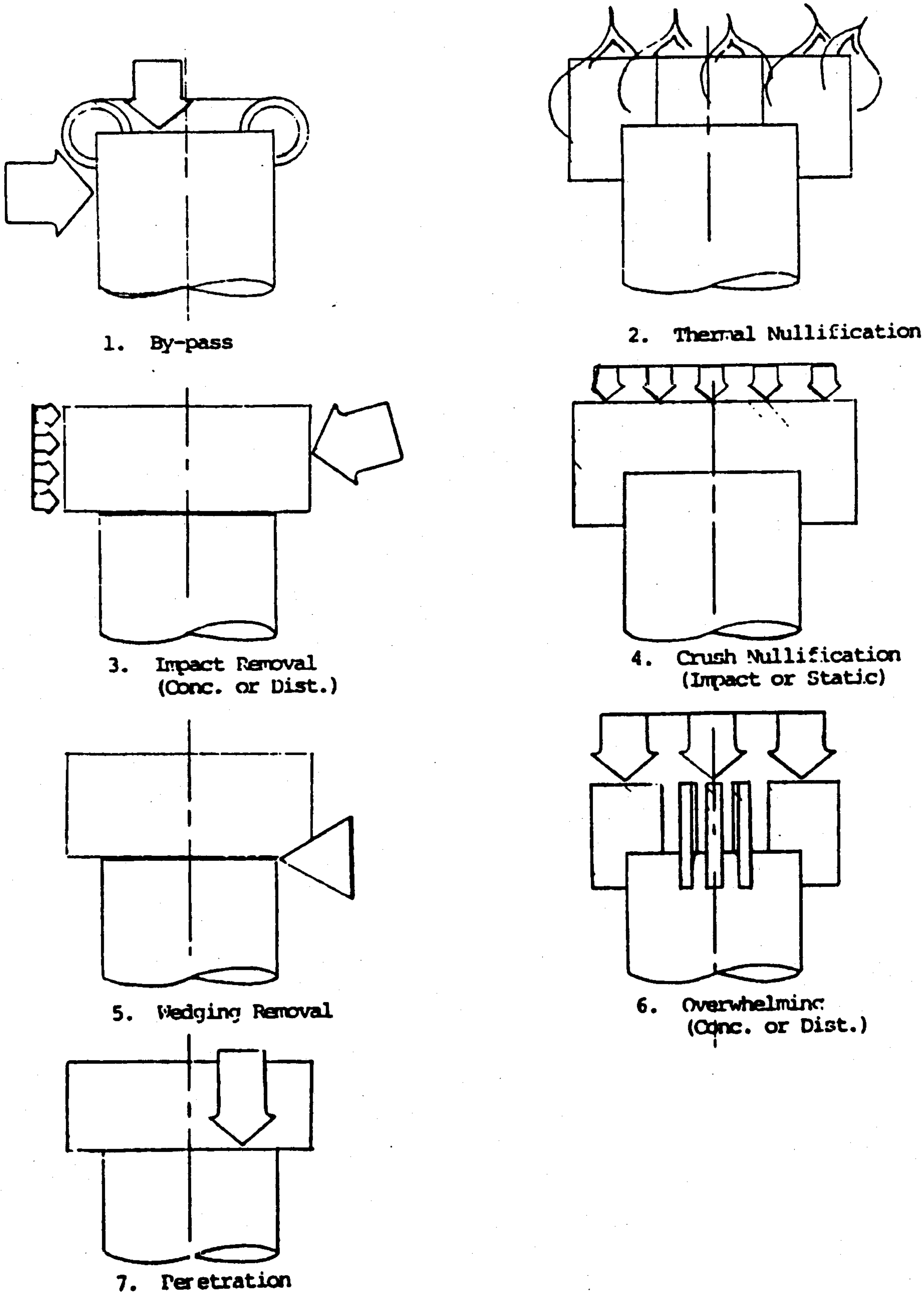

FIGURE 13. INFLUENCE OF IMPACT ENERGY ABSORBER DESIGN ON POSSIBLE MODES OF INTERACTION WITH ACCIDENT ENVIRONMENT

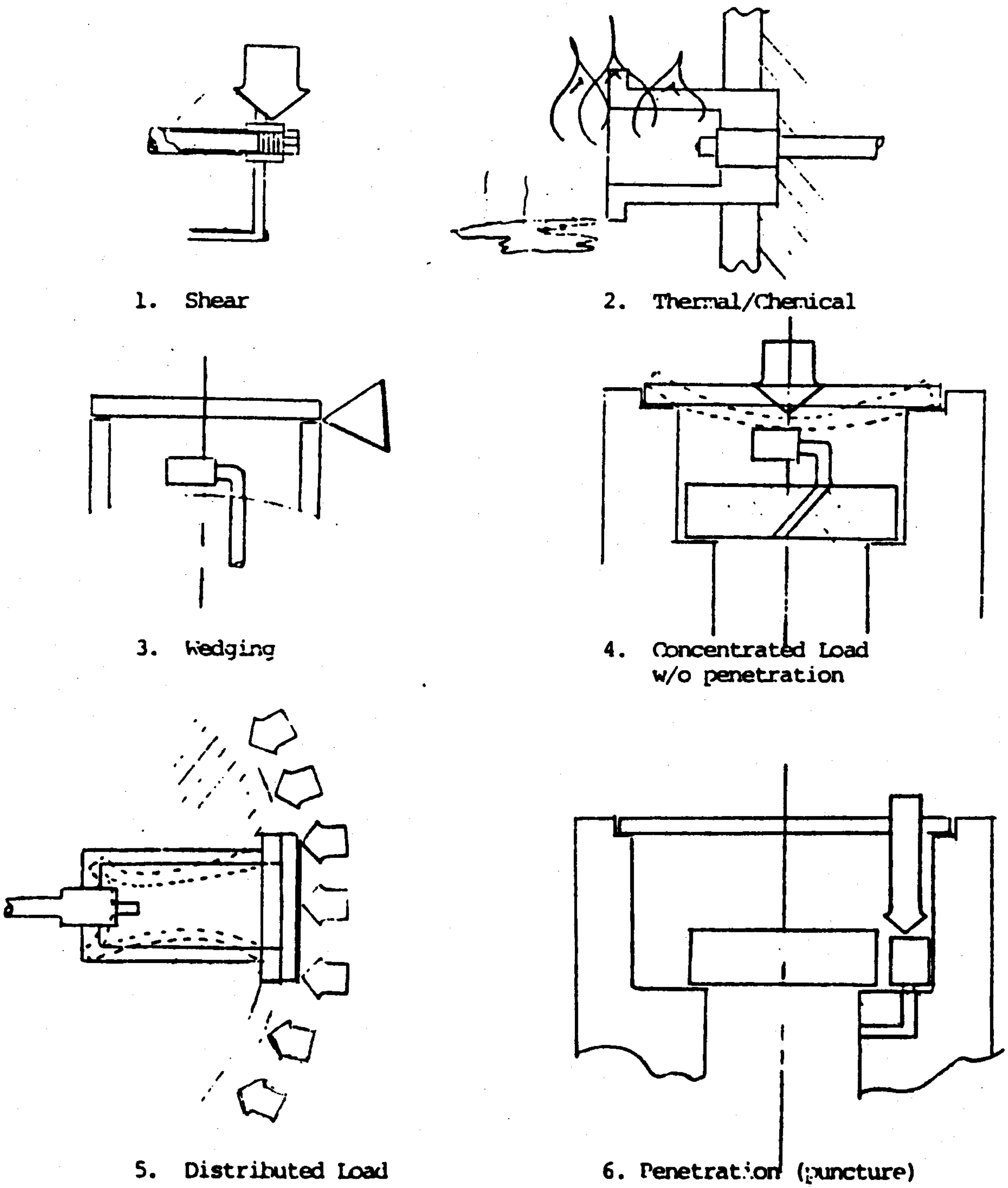

FIGURE 14. INFLUENCE OF VALVE PENETRATION DESIGN ON POSSIBLE MODES OF INTERACTION WITH ACCIDENT ENVIRONMENT

APPENDIX B

EGGERS'S TABLE OF EXTREMELY SEVERE ACCIDENT LOADS

Recommended List of Extremely
Severe Accident Environments
For Highway and Railroad Modes

The results of the preceding structural and thermal analyses provided the basis for formulating a recommended list of extremely severe accident environments. This list of accident environments is presented in Table 26 and includes both the railroad and highway modes of transport. These extremely severe accident environments and the corresponding estimates of the loads imposed on the various packages analyzed will be the basis in Task IV for formulating a set of physical tests (mechanical and thermal) to represent these accident environments.

TABLE 26. RECOMMENDED SET OF EXTREMELY SEVERE ACCIDENT ENVIRONMENTS FOR HIGHWAY AND RAILROAD MODES

ACCIDENT CLASSIFICATION	EXTREMELY SEVERE ACCIDENT ENVIRONMENT	
	RAILROAD MODE	HIGHWAY MODE
1. Crushing (long duration)	200,000 lbs bearing on package; crushing object is 3 in. wide, locomotive sill with locomotive supported at one end.	60,000 lbs bearing on package; crushing object is 4 in. wide long chassis beam with full weight of legal weight trailer and cargo bearing on package.
2. Impact (package stationary, impacting object moving)	a) Impact by sill of 200 ton locomotive with bounding force of 4,640,000 lbs b) Impact by sill of 150 ton railcar with bounding force of 3,600,000 lbs	a) Impact by sill of 200 ton locomotive with package at railroad crossing; bounding force limit of locomotive sill is 4,640,000 lbs, estimated force for 60 mph impact is 2,000,000 lbs. b) Impact by cargo – 21 in. I-beams at velocity of 60 mph.
3. Impact (package moving, impact object moving or stationary)	Package falls 60 to 80[1] feet onto concrete pavement resulting in bounding force which is a function of package weight and dimensions.	Package falls 70 to 90[2] feet onto concrete pavement resulting in bounding force which is a function of package weight and dimensions.
4. Thermal Load (Concentrated)	Torch with diameter of 6 feet at 12 feet from source impinges on package for duration of 0.5 to 1.0 hour; torch parameters based on experimentally measured values.	Torch with diameter of 6 feet at 12 feet from source impinges on package for duration of 15 to 30 minutes; torch parameters based on experimentally measured values.
5. Thermal Load (Distributed, Enveloping)	Wall of flame adjacent to package (10 feet) for duration of 2 to 10 hours; fire based on LPG flame temperature of 1600 F. Engulfing fire with duration of 0.5 to 2 hours; fire based on LPG flame temperature of 1600 F.	Wall of flame adjacent to package (10 feet) for duration of 0.5 to 2 hours; fire based on LPG flame temperature of 1600 F. Engulfing fire with duration of 0.5 to 1 hour; fire based on LPG flame temperature of 1600 F.
6. Thermal Isolation	Package covered by coal with a covering thickness of 3 feet on 70 percent of surface and remainder of package in contact with ground; duration of coverage is 24 hours.	Not applicable since only short duration burial events have been reported.

(1) The maximum reported falling distance in the railroad accident literature was 76 feet.
(2) The maximum reported falling distance in the highway accident literature was 89 feet.

APPENDIX C

POST DRAFT ACTIVITY

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C.1 SUMMARY

We knew the findings of the Modal Study review were controversial and asked that the report remain a draft pending discussions and further assessment. We undertook some analyses to confirm the opinions we developed in our original review. In addition, limited post-draft discussions with the authors of the reviewed reports and with personnel from the NRC led to the review of a number of additional reports. The principal findings of this additional work are highlighted below with further details in the subsequent sections of this appendix.

We identified several limitations associated with the two-dimensional (2-D) finite element models used in the LLNL study. The first subsection of this appendix presents the results of analyses of the limitations of the 2-D model used. The analysis supports our contention that the strains for LLNL's side impact analyses may have been understated due to the coarseness of the grid used in their model. We also noted that the rail vehicle impact case was analyzed with a 2-D model as an evenly distributed load across the length of the cask whereas we felt that assuming a concentrated load would be more conservative. Our results indicate that concentrated loads from non-flat surfaces can produce higher strains even though the structure to which it is impacting may have a lower force generating capacity.

The second subsection of this appendix explores the characteristics of the 100-mph train collision with a spent nuclear fuel cask that was conducted in the United Kingdom. During the course of discussions on our draft report, we were referred to the U.K. test as evidence of the crashworthiness of SNF transport casks. We reviewed the facts surrounding that collision demonstration and the details of the 'Magnox flask' that was used in the demonstration. It was concluded that the test was irrelevant with respect to a head on collision between a North American railroad locomotive and the LLNL candidate cask.

The third subsection of this appendix involves the review of several Safety Analysis Reports (SARs). It was suggested to us that the analyses presented in SARs provide a comprehensive treatment of a cask's response to normal and hypothetical accidents. Upon review of the contents of several such reports we conclude that the phrase "*hypothetical accident conditions*" as used in relation to SARs is simply a reference to the regulatory tests as set out in U.S. 10 CFR 71. Therefore, in terms of mechanical loading, the only criteria which rail casks are evaluated against are Drop Test I (a 30 foot drop onto a flat unyielding surface) and Drop Test II (a 40 inch drop onto a 6 inch diameter mild steel rod). Drop Test III, a dynamic crush test, is not applicable to rail casks in accordance with the requirements of U.S. 10 CFR 71. No evidence was found within the reviewed SARs to indicate that other accident scenarios were typically either considered or analysed. It was also indicated to us that impact limiter retention must be demonstrated to meet regulatory requirements and that significant analyses are typically available in the supporting SAR documents. However, these analyses would appear to be consistently focused on demonstrating retention throughout the regulatory tests and do not consider the consequences of impacts with other significant bodies prior to the test impact.

C.2 2-D FINITE ELEMENT ANALYSES USED IN THE "MODAL STUDY"

We identified several limitations associated with the two-dimensional (2-D) finite element models used in the LLNL study.

C.2.1 Density of Finite Element Grid

We expressed concern that the 2-element thickness of the inner shell may not capture bending stresses since the three shell layers (steel-lead-steel) can move independently. To explore this we analyzed a simple cylinder of the same properties and dimensions as the inner steel shell of LLNL's candidate cask. We used the same 2-dimensional finite element analysis as LLNL except we used LLNL's 2-element thickness for one model and a 6-element thickness for a second. We found that the more detailed model reached 0.2% strain at a load force that was about one half of that required for the 2-element-thickness model. The results support our concern that the strains for LLNL's side impact analyses may have been understated due to the coarseness of the grid used in their model.

C.2.2 Concentrated vs. Distributed Loads

We expressed concern that mostly flat surfaces were analyzed and that the rail vehicle impact case was analyzed with a 2-D model as an evenly distributed load across the length of the cask. We felt that a concentrated load would be a more conservative assumption. We compared the results of an impact with an unyielding flat surface in two orientations:

1. a 3-inch thick unyielding surface evenly contacting the cask along its length (similar to the LLNL locomotive sill impact) and;

2. the same 3-inch thick surface rotated 90 degrees so that the impact was concentrated at the center of the cask (a rolled over locomotive sill impact).

A cask model similar to LLNL's (i.e. an open ended, empty, steel-lead-steel cylinder) was used for the first two 2-D cases. The same cask was then modeled in 3 dimensions with steel end-plates added for the third case (concentrated load). The 3-D model was simulated for 10 ms while the 2-D models were simulated to bounce-off. The results are illustrated in Figure C-1. The relative strain ratios indexed to the 3-D sill at 10 ms were:

	flat surface	distributed sill	concentrated sill
@ 30% KE	33 %	35 %	100 %
@ 100% KE	72 %	93 %	N/A

The higher strain achieved by the concentrated load was developed with a lower reaction force at the impact interface. The average loads over the first 10 ms impact time were: 3.35 million lb., 3.15 million lb. and 0.68 million lb. for the flat, distributed-sill and concentrated-sill respectively.

Thus, concentrated loads from non-flat surfaces can produce higher strains even though the structure may have a lower force generating capacity.

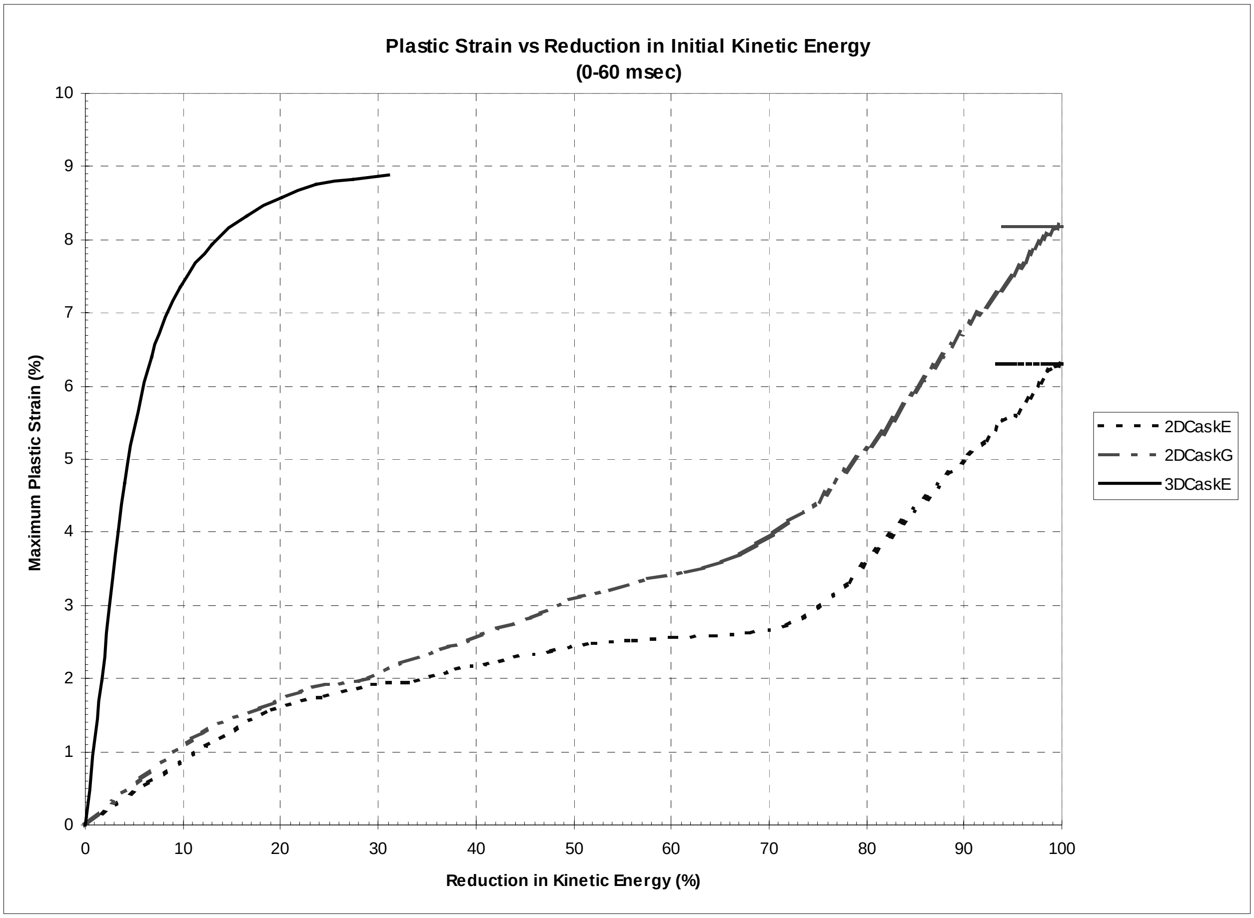


Figure C-1 Plastic Strain Vs Reduction in Kinetic Energy (0-60 msec)

C.2.3 Importance of Impact Limiters

We expressed concern that the impact limiters were vital to cask survival but that there was no test requirement for retention of the impact limiters when exposed to glancing blows. We used LLNL's surface hardness properties and their method of impact analysis of softer surfaces to assess the survivability of a cask without an impact limiter attached in collision with flat surfaces. The results for three surface hardnesses were considered. If the cask only impacts with 'soil' when its limiter is detached, it would experience lower forces than it would in the regulatory impact test with the limiter attached. However with harder surfaces, the impact forces are greatly enhanced. The 40-'g' design threshold is reached at 32.6 mph under the base test conditions with limiters attached. Without a limiter on the impact end, the 40-g limit would be reached in a 2.7-mph impact with the same unyielding flat 'test' surface. If a flat 'soft rock' is impacted, the allowable impact speed is raised from 2.7 mph to 3.8 Mph.

C.3 THE BRITISH RAIL TRAIN-CASK DEMONSTRATION COLLISION

During the course of discussions on our draft report, we were told of a full-scale 100-mph train collision with a spent nuclear fuel cask conducted in the UK. We have reviewed reports of that collision and have made comparisons between the cask used in the demonstration and the LLNL candidate cask. The UK test involved a 'Magnox flask' which is quite different in design and payload capacity. The Magnox flask is illustrated in Figure C-2.

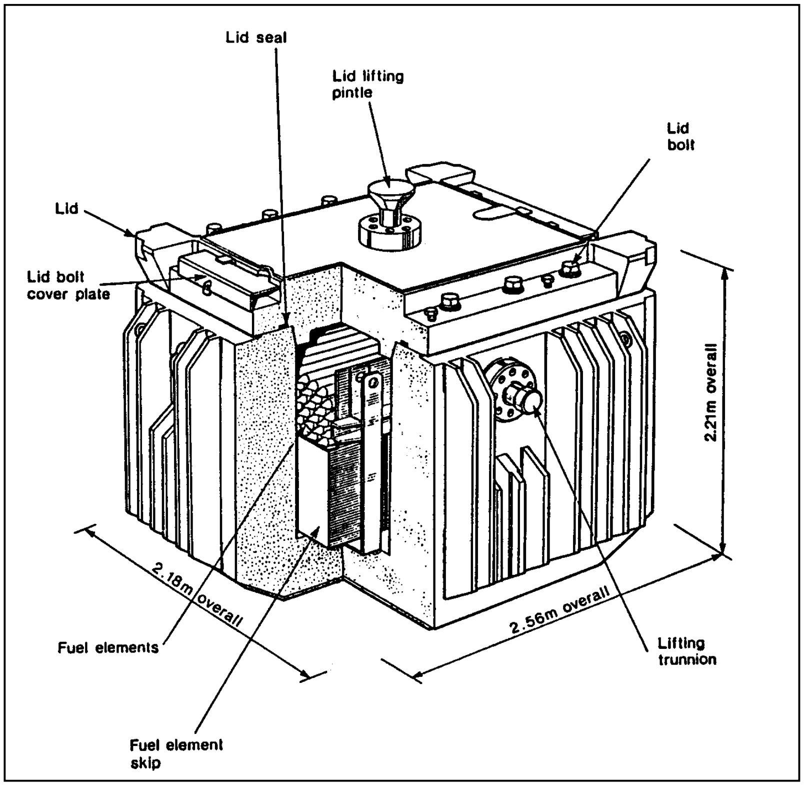
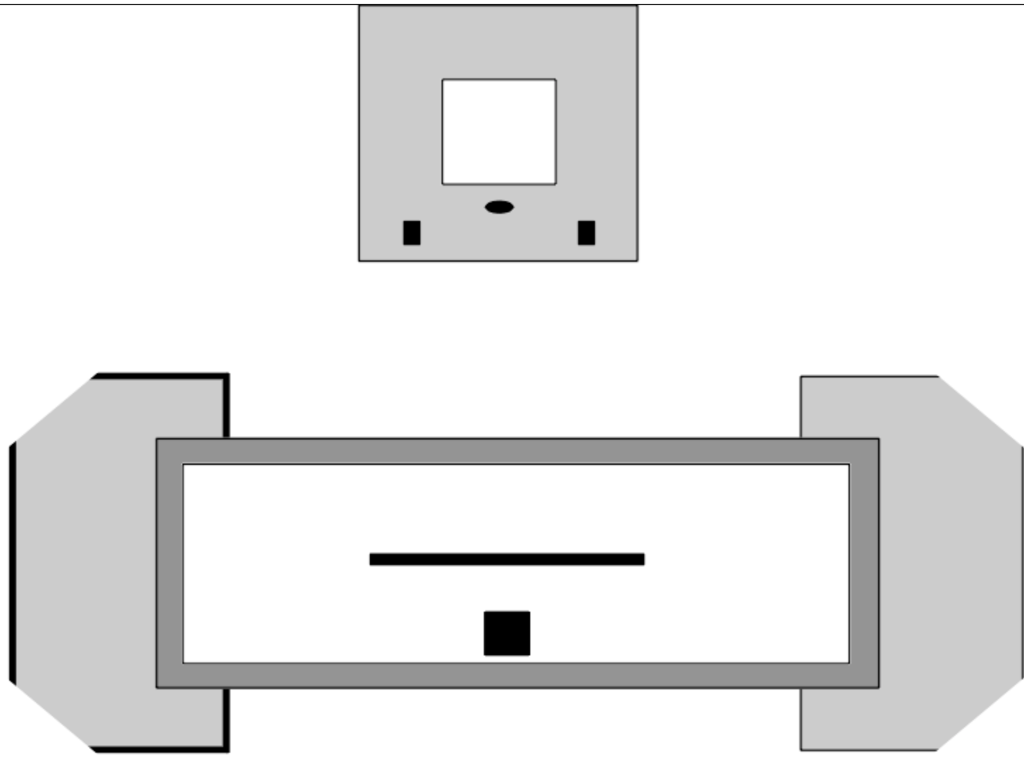


Figure C-2 Illustration of Magnox Flask.

The Magnox flask measures about 7.2-feet * 7.2-feet * 8.4-feet with walls in the order of 16-inch-thick solid steel construction. It is designed with steel fin impact limiters and can withstand significant 'g' loads (~ 170 g).

The reports of the demonstration test indicate that the cask underwent an initial 30-g impact with the draw-hook and two frames of the locomotive's front bogie. The orientation of the cask was such that the three points of contact were aligned with the bottom and side walls of the flask. Thus, the main impact was aligned with the 9-foot depth walls of 16-inch thick steel. The initial contact was below the center of gravity of the flask and it rotated upwards into the cab area of the locomotive. The initial impact with the stiff components of the locomotive peaked in 9 milliseconds. The remaining 171 milliseconds of the impact duration (roughly corresponding to 99% of the impact energy) involved the softer upper body of the locomotive.

Figure C-3 compares the locomotive collision geometry of the Magnox and LLNL casks.



Upper: Magnox flask (draw-hook and bogie frame contact points)
Lower LLNL's candidate cask (loco sill and coupler impact points)

Figure C-3 Impact Geometry from Impacting Locomotive's Viewpoint.

One can see that the Magnox impact points are aligned with 9-foot deep steel walls and below the center of gravity. On the other hand, the LLNL cask impact would be closer to its center of gravity and would bypass the impact limiters directly contacting the composite wall of 3.5-inch steel / 4-inch lead / 1.5-inch steel.

In addition:

- the Magnox flask is designed to withstand a 170 'g' impact load compared with 40 'g' for LLNL's candidate cask (the lower 'g' limit is achieved through the use of softer impact limiters);
- the mass of the Magnox flask is about two thirds that of the LLNL candidate cask, and;
- a North American locomotive is designed to develop at least twice the load magnitude as a UK locomotive.

All of these factors contribute to a conclusion that the Magnox flask demonstration collision is irrelevant to the LLNL's candidate cask.

C.4 REVIEW OF SAFETY ANALYSIS REPORTS

As our review was confined to survivability, the NRC was asked for information on the consequences of severe events as well as aspects of the licensing process dealing with those situations we believe are not covered by the design criteria (such as the ability of the cask to withstand crush loads and certain types of fires). The NRC's response reasserted the DOE position that the cask would survive any foreseeable railway accident and thus consequences were of little concern. The response also indicated that license applications must be accompanied by safety analysis reports (SAR's) that provide significant additional details. Of particular interest in the NRC response was the indication that SARs must address "normal and hypothetical" accident scenarios, that design criteria require that casks provide protection from off-normal accidents, and that if impact limiters are sacrificial, their presence during impact must be demonstrated. We reviewed several SAR's to better understand the NRC's response.

A limited review of selected Safety Analysis Reports (SARs) prepared and submitted to the NRC for certification of casks designed and/or used for movement of spent nuclear fuel by rail transportation was undertaken. Our specific interests were to identify:

- the nature and extent of accident conditions considered throughout analyses supporting certification submissions to the NRC;

- the severity of tests, and analysis techniques used, to assess side puncture/localized impacts which could be related to railway coupler impact loads;

- to collect further information on impact limiter construction, attachment and testing which would support assessment of impact limiter retention capability during a realistic rail car pile up; and

- to collect further details of typical end closure and internal structural support members.

Three representative SARs were examined during a visit to the NRC Public Documents Room (PDR) in Washington D.C. Each is discussed below.

C.4.1 SAR 71-9023

The container analysed in SAR 71-9023 is designed as a rail shipment cask providing "dry shipment" and "double containment" and may be configured to transport either ten (10) PWR or twenty four (24) BWR type light water reactor spent fuel assemblies. The fully loaded weight is 194,000 lbs. The document reviewed was dated November 1991, however it is evident from some notations that this design and analysis (or some portions) date back to at least 1974.

The container analysed in SAR 71-9023 is cylindrical in construction with a 0.75-inch thick 304 Stainless steel inner shell, a 6-inch thick chemical lead Gamma shielding, a 2-inch thick 304 stainless steel outer shell and a 9-inch thick water neutron shield contained by a 0.75-inch thick stainless steel water jacket having heat transfer ribs on both the inside and outside surfaces. Its inner closure head is constructed with 3-inch thick depleted uranium Gamma shielding sandwiched between 0.75-inch and 3-inch thick layers of 304 stainless steel, which is bolted in sixteen (16) locations using 1.75-inch long studs. The outer closure head is manufactured of 2.5-inch thick 304-stainless steel, which is bolted in twenty-four (24) locations with 1.25-inch long bolts.

The impact limiters are constructed using three (3) concentric aluminium shells filled with balsa wood. They are bolted on to either end of the cask in thirty-six (36) locations using 2-inch long socket head cap screws equally spaced around a 67.25-inch diameter.

Much of the SAR relies on analytical work, which examines individual components and regions of the design. Some Finite Element Analysis (FEA) has been performed using ANSYS (Update 155B Rev. 2), although it did appear that these were primarily used for thermal analyses. In these models, thin, elastic, axisymmetric shell elements (ANSYS element STIF 11) were used where the shells do not contact lead. Isoparametric quadrilateral ring elements (ANSYS STIF 42) were used to model the shell/lead interface and the entire lead-shielding layer.

The SAR states in the portion of documentation related to 71.34(a)(2), on Hypothetical Accidents, that:

> *"Model testing was not done. The mechanical properties of the materials of construction of the cask and the shock absorber are well known. Analytical methods of predicting cask and shock absorber response to impact loads have been developed and correlated to actual data. Considering this, and the fact that conservative assumptions have been made throughout the analysis, mathematical analysis has been used to satisfy this subpart."* [pg IV-10]

The SAR also states in the portion of documentation related to 71.37(a), on Model Testing, that:

> *"Model testing has not been done to evaluate the cask by the criteria specified in 71.39. Damage to the package, following the hypothetical accident described in Appendix "B" of this part, has been evaluated by analytical methods. See response to 71.34(a)(2) above."* [pg IV-13]

We note that it would be extremely difficult to perform an IAEA regulatory 9 metre drop on a full scale cask weighing nearly 200,000 lbs. However, scale model testing is often done these days to demonstrate compliance.

Some 1/8-scale model testing of impact limiters has been done to examine their performance. These were looking specifically at deformation and retention performance during regulatory tests (i.e. 9-metre drop and pin drop) and did not specifically address with any rigour other loading and accident scenarios which might dislodge the impact limiters.

The brief page or two devoted to the pin drop test evaluated the failure load of, or maximum load produced by, a regulatory pin and then assessed the minimum required outer plate thickness to resist puncture by that load.

C.4.2 SAR 71-9206

The design of the container analysed in SAR 71-9206 seems to go back to the 1985 time frame, with the Revision 6 SAR (which was reviewed) issued on March 1994.

This container is essentially a single-walled cylinder constructed of forged 9.25-inch thick carbon-steel walls (SA-350, Gr. LF3) with an integrally welded forged carbon steel bottom of 8.25-inch thickness. The lid is also forged of carbon steel, is 8.5 inches thick and affixed to the shell by forty-eight (48) 1.625-inch long bolts (SA-320, Gr. L43). Impact limiters are constructed of Balsa and red woods with an exterior steel sheath (SA-516, Gr. 60) and are each affixed to the cask using four (4) 1.5-inch bolts and two (2) 1.5-inch diameter pins.

The documents included non-disclosure requests and it appears that certain information contained within the SAR have been withheld from the publicly accessible documents. It would appear that they are particularly sensitive regarding certain design and analysis details of the basket assemblies.

This SAR has made extensive use of FEA, using the ANSYS code, to demonstrate compliance with regulations. These were conducted using both 2-D and 3-D models depending upon the particular requirements of the analyses. 3-D models were used to examine stresses expected to develop during 30-ft. drops onto unyielding surfaces (i.e. regulatory drop test). They have used three elements through the wall thickness, which they indicate to be adequate for accurate determination of membrane and “linearized” bending stresses. They appear to have paid attention to locations where high stress gradients are expected and applied some mesh refinement.

The cask’s puncture resistance to a regulatory pin drop test was evaluated analytically, without benefit of scale model testing or FEA. This was done by determining the equivalent ‘G’ load (6.3g in this case) and evaluating the minimum wall thickness necessary to withstand the local shear stresses caused by the pin impact. They indicate this minimum thickness to be 2.52 inches. They have also determined the maximum reaction force that a 6-inch diameter regulatory pin may develop during a 40-inch drop to be 1,415,000 pounds. This was calculated assuming the pin behaves as an “elastic perfectly plastic” material with 50 ksi yield. This analytical approach seems essentially similar to that taken in the previously outlined SAR.

The designers of this cask seem to have paid great attention to the design and analysis of the fuel baskets and their support structure. They also have designed spacers to be used in locations where baskets are not placed, or can not be placed. These analyses were performed using FEA techniques.

C.4.3 SAR 71-9235

The container analysed in SAR 71-9235 is a dual walled, lead-lined cylinder which appears to be very similar to the hypothetical “MPC” portrayed in the NRC “Modal Study”. The outer shell is 2.65-inch thick 304 stainless steel. The inner shell is 1.5-inch thick 304 stainless steel. The

Gamma shield is 3.70-inch thick chemical lead. Neutron shielding is provided by a solid synthetic polymer, NS4FR, on each end and around the outer shell.

The analysis of the container portrayed in the Revision 9 SAR dated December 1996 was quite extensive. In fact, this design appeared to be much more rigorously analysed than the other two designs previously examined. The work included a considerable amount of FEA using the ANSYS code for thermal and structural analyses of 30 ft. drop tests. They appear to have used the SCANS code to evaluate a range of oblique drop angles to determine the worst drop orientation (i.e. 0-90 degrees in 15-degree increments). In addition, they have conducted quarter-scale drop tests.

A common thread was maintained with the other SARs reviewed in that the effects of cask puncture were evaluated using purely analytical means. Specifically, they calculate the maximum pin reaction force to be 1,329,000 lbs during a regulatory pin drop test (assuming 47,000-psi dynamic flow stress). Then, they evaluate the required minimum outer shell thickness to withstand application of this load without puncturing using the "Nelms" equation and arrive at 2.58-inch. They conclude:

> *"For the pin puncture event at the cask midpoint, local deformation may occur in the region of the impact; however, the cask is demonstrated to have sufficient thickness to resist puncture."*

The impact limiters used in this design are constructed from redwood and balsa wood encased in stainless steel shells. They are attached to the cask using sixteen retaining rods on each end.

C.4.4 Conclusions Drawn from the SAR Review

1) The phrase "*hypothetical accident conditions*" as used in relation to SARs is simply a reference to the regulatory tests as set out in U.S. 10 CFR 71. Therefore, in terms of mechanical loading, the only criteria which rail casks are evaluated against are Drop Test I (a 30 foot drop onto a flat unyielding surface) and Drop Test II (a 40 inch drop onto a 6 inch diameter mild steel rod). Drop Test III, a dynamic crush test, is not applicable to rail casks in accordance with the requirements of U.S. 10 CFR 71. No evidence was found within the reviewed SARs to indicate that other accident scenarios were typically either considered or analysed.

2) The impact force developed during a regulatory pin drop test is limited by the strength of the 6-inch diameter mild steel pin. In all SARs reviewed, the analytical procedure followed a similar approach. First, the failure load of a regulatory pin was analysed and then the minimum shell thickness required to resist that applied load without failing was calculated. These values were on the order of 1.4 million-pound peak puncture force and minimum shell thickness of approximately 2.58 inches. No results of analyses were found within the SARs to provide additional quantification of the degree of puncture resistance to higher loads if developed during an accident.

3) Analysis of impact limiter retention focused upon demonstrating retention during regulatory drop tests rather than demonstrating a more general ability to resist dislodgement by other impacts that might reasonably be envisioned. It is a requirement that impact limiters remain in place during the regulatory drop tests.